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ABSTRACT

The National Research Council's Aeronautics and Space Engineering Board conducted a workshop in January 1984 to project what the state of knowledge of aeronautical technology could be in the year 2000 if necessary supporting resources were made available. Eight panels were organized to assess possibilities in the areas of: (1) aerodynamics; (2) propulsion; (3) structures; (4) materials; (5) guidance, navigation and control; (6) computer and information technology; (7) human factors; and (8) systems integration. Participating in these panels were experts from academia, industry, and government. Projections were made that would serve as a base for planning future research and facilities and also as an insight base on the state of the art in aeronautical technology for civil and military planners of air vehicles and systems. Proceedings from this study are arranged into three sections: (1) summaries of the principal findings of each panel; (2) individual panel reports; and (3) an appendix containing panel recommendations regarding requirements for supporting research and facilities. A bibliography and glossary of aeronautical terms and codes are also included. (ML)

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Report of a Workshop

Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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Aeronautics Technology Possibilities for 2000:
Report of a Workshop

Workshop on Aeronautical Technology: A Projection to the Year 2000
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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AERONAUTICS TECHNOLOGY POSSIBILITIES FOR 2000

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PREFACE

At the request of the National Aeronautics and Space Administration, the National Research Council's Aeronautics and Space Engineering Board conducted a workshop in January 1984 to project what the state of knowledge of aeronautical technology could be in the year 2000 if necessary supporting resources were made available.

The study was intended to provide a basis for planning future aeronautical research and technology programs and identifying test facilities and capabilities needed to support the projected technology advancements. Some 80 experts participated in the study. They were organized into eight panels in the areas of aerodynamics; propulsion; structures; materials; guidance, navigation, and control; computer and information technology; human factors; and systems integration.

This document consists of three main parts: (1) an Introduction and Summary highlighting the principal findings of each panel, (2) the individual panel reports, and (3) an appendix containing panel recommendations regarding requirements for supporting research and facilities.

ACKNOWLEDGEMENT

Special recognition and thanks are due the following organizations and individuals for the excellent support provided to the chairman and participants of the workshop. Without their valuable assistance, willing cooperation, and warm hospitality, the task of the participants would have been far more difficult and much less productive.

Excellent facilities and equipment were provided the workshop by the University of Texas at Austin; the Joe C. Thompson Conference Center, University of Texas; and the School of Law of the University of Texas. These arrangements were made possible through the personal efforts of the following individuals from the University of Texas: Peter T. Flawn, President; Sam H. Hall, Assistant Dean, School of Law; Byron D. Tapley, Aeronautics and Space Engineering Board member and D. R. Woolrich Professor, Department of Aerospace Engineering, and by Glenn Greenwood, Conference Coordinator of the Joe C. Thompson Conference Center.

In addition, the workshop participants (including the chairman, panel leaders and members, rapporteurs and liaison representatives) are to be commended for their personal contributions and dedication to the task before, during, and after the workshop that made the study and this report possible.

Finally, it is important to recognize the personal contributions of the ASEB staff members and others who provided the highest level of administrative support during the organization and conduct of the workshop and in the subsequent completion of this report. Special thanks are due Marlene R. Veach and Julie A. Ferguson of the ASEB staff, and also to Delphine D. Glaze, Colleen Kelly, Chris Rowland, Vivian A. Scott, and Elaine Wheeler.

Aeronautics & Space Engineering Board

INTRODUCTION AND SUMMARY

During late 1982 and early 1983, discussions were held between the Aeronautics and Space Engineering Board (ASEB) of the National Research Council and the National Aeronautics and Space Administration's Office of Aeronautics and Space Technology concerning NASA's need for a sound long range plan for acquiring future test facilities. These discussions led to the idea that a comprehensive study of the potential of aeronautical research and technology (R&T) development could provide the basis not only for facility planning, but also for long-range guidance of R&T programs and could also establish strong justification for support of aeronautical research and technology. Thus, in 1983, NASA asked the ASEB to conduct a workshop to provide an opportunity for innovative "freethinkers" to come together and project the state of knowledge and capability in specific technological areas by the year 2000, assuming that adequate resources will be available. The projections were viewed as serving several specific purposes: (1) providing a base for planning research and future facilities needed to support and capitalize fully on the projected technologies, as well as to develop advanced vehicles that might evolve; and (2) providing some insight on the possible state of the art in aeronautical technology by the year 2000 for civil and military planners of air vehicles and systems.

The workshop was organized into seven technology panels in aerodynamics; propulsion; structures; materials; guidance, navigation, and control; computer and information technology; and human factors. Each panel attempted to project the state of knowledge and resulting capabilities in its respective field. It was recognized that there was a close interdependence in the subjects being studied by the various panels. For this reason, time was set aside during the workshop for the panel leaders and members to exchange information and to coordinate their views on interdisciplinary issues. Consequently, although the panel reports primarily address a specific area of technology, in several instances they also contain information closely related to the area of interest of one or more of the other panels. An effort has been made to cross reference some of the interpanel information, but a reader having a particular interest in a specific area of aeronautical technology might find it worthwhile at least to scan the table of contents of all panel reports to ensure that any additional information of interest is not overlooked.

Using the projections of the technology panels, an eighth panel (in the area of systems integration) attempted to conceptualize how the projected technologies could be utilized/integrated to provide advanced aeronautical system capabilities. The preliminary conceptual vehicle projections developed by this panel at the workshop provided the basis for a separate follow-on ASEB study by an ad hoc Vehicle Applications (VA) Panel. Using the workshop information as a starting point, the VA Panel was to assess and analyze the projected technology

and systems advances in the context of potential vehicle applications and concepts for the 2000+ time period. The findings of the Vehicle Applications Panel are contained in a separate report prepared by that group.

It should be noted at the outset that, in conformity with the intent of the workshop, the conclusions and recommendations contained in this report are based almost entirely on judgments of the panels of experts who were carefully selected from academia, industry, and government to provide as balanced a perspective as possible. In addition, the report frequently gives numerical estimates which, it should be recognized, are likewise based on the expert opinion of the workshop participants.

Each technology panel was specifically charged to

- o assess the current and projected state of the art in its field including technology target areas and new ideas, and
- o identify opportunities for advances in aeronautics technology that were seen as achievable by the year 2000. In particular, the effort was not to be limited to "requirements-driven" technology.

The Systems Integration Panel was charged to:

- o review the state of knowledge projected by each of the technology panels,
- o identify vehicle concepts that could be developed using the projected advanced technology that would most benefit civil and military aviation, and
- o evaluate the current state of knowledge of systems integration as a discipline and project anticipated advances in this area.

A summary of the principal findings of each of the panels follows.

Aerodynamics

The prospect for significant aerodynamic technology advancement by the year 2000 is bright. Rapid development in computational fluid dynamics (CFD) capability, coupled with advanced unobtrusive instrumentation, will provide vastly improved understanding of fundamental flow phenomena. Progress in CFD will provide for modeling of increasingly complex flows, including development of improved turbulence models and full Navier-Stokes simulation. A more thorough understanding of turbulence, transition, separation, vortex dynamics, and the physics of hypersonic flow will permit quantum advancements in aerodynamic design capability. Goals expected to be achieved over the next 15 years include development of a usable model for transition and

turbulence structure; improved understanding and modeling of parameters governing 3-D separation and reattachment; and increased knowledge of vortex formation, interaction, and breakdown phenomena.

These advances will provide the key for optimizing the new reduced observable designs that will dominate emerging military vehicle concepts and for improving conventional aircraft performance. Some potential improvements include

- o Drag reduction
  - -- Laminar flow control (LFC) through active and passive concepts, providing 20 to 25 percent reduction in aircraft drag.
  - -- Turbulent flow control through nonplanar wall, turbulence modification devices, and pressure gradient modification, resulting in 25 to 30 percent reduction in subsonic fuselage friction drag (C_f) and 10 to 15 percent at supersonic speeds.
  - -- Wave drag reduction up to 40 percent for fighter configurations.
  - -- Drag due to lift reduction of 30 to 40 percent through planform and structural arrangements.
  - -- Significant interference drag reductions for component junctures and stores carriage,
- o Vortex management
  - -- Development of departurefree configurations by active vortex control.
  - -- Development of nonmovable fluidic control surfaces.
  - -- Reduction of 40 to 50 percent in separation time for airport takeoff and landings through wake vortex alteration,
- o Aero/propulsion integration
  - -- Substantial reductions in takeoff and landing distances and/or substantial increases in payload range characteristics through use of thrust vectoring/thrust reversing.
  - -- Doubling of the usable maximum lift through propulsive lift concepts that employ low engine bleed rates.
  - -- Adaptive inlet and nozzle integration concepts to reduce weight and improve performance and survivability.

-- Advances in high-speed turboprops, supersonic through-flow fans, ejector thrust augmentation, and hypersonic aero/heating effects,

-- Helicopter rotor designs with improved performance, low noise, and low vibration loads, and

o Configuration synthesis

-- Development of completely integrated design synthesis programs.

-- Significant integration of computing power in the aircraft itself to provide real-time aerodynamic and structural adaptability of the aircraft to give "birdlike" adaptive flight.

-- Establishment of a substantial data base for new, unconventional vehicle shapes.

Propulsion

The benefits to be expected from advanced propulsion technology will provide both economic gains and increased capability. By shortening the development cycle and enabling improved design precision, advanced technology will allow a more timely response to market needs.

Flight in the unused zones can be made routinely available and economical by development of hypersonic ramjets and a range of variable cycle engines. For "conventional" turbofan and turboprop engines, the advantages of reduced fuel consumption that would accrue from advanced propulsion technologies are substantial (15 to 20 percent in commercial turbofans, 10 percent for high-performance military aircraft). In addition, a higher thrust-to-weight ratio, lower cost, and/or longer engine life are possible.

Advances in five critical technical areas--propulsion systems, computational fluid dynamics (applied to internal flows), materials, heat transfer, and instrumentation and controls ("smart" components) --will drive improvements.

Specific resulting improvements could include

o capability to compute three-dimensional viscous flow in fans, compressors, and turbines with sufficient dispatch to make the process useful in design;

o materials able to withstand temperatures 400°F to 600°F higher than today's materials;

- o enhanced heat transfer prediction capability, which will lead to substantial reductions in development time and cost for the hot sections of engines. Average temperatures of 3000°F components will be predicted within 10°F;

- o availability of sensor technology for comprehensive hot section measurements and ability to perform in situ structural assessment with highly reliable sensors;

- o continued microelectronic development that will permit onboard computational capacity for "smart" components in advanced controls resulting in optimal performance;

- o efficiencies of 80 to 90 percent for moderate-size compressors;

- o mechanical components (main shaft bearing and seals) capable of meeting reliability requirements at bearing rotational speeds of 3.5 million DN;

- o availability of a polyimide composite system that would endure engine temperatures well beyond the presently targeted 700°F material (possibly as high as 800°F to 900°F) to provide increased operational capability at reduced weight and cost;

- o availability of blading to avoid excessive resonant response to periodic flow variations and ability to predict overall engine response to transient events such as blade loss, hard landings, and sharp maneuvers; and

- o solving of critical problems associated with high-speed propulsion for the Mach 3.5 to 12 regime.

Enhanced research and technology development will provide major benefits to advanced propulsion systems for applications such as high speed turboprops, short takeoff and/or vertical landing (STOVL) aircraft, convertible rotorcraft, low radar signature aircraft, and hypersonic and transatmospheric vehicles.

Structures

Major advancements are projected as obtainable by the year 2000 in five major structural technology areas: adaptive structures, thermal structures, damage tolerant structures, propulsion structures, and advanced structural concepts. Adaptive structures, in which the vehicle configuration automatically adapts or can be controlled to adapt its shape to obtain optimum performance throughout the flight envelope, will permit greater maneuverability; lower structural weight coupled with advances in aerodynamics and control technology will permit "birdlike" flight. Development of structures that can cope with any thermal environment will open the practical speed range of

aircraft to above Mach 5. Advances in energy-absorbing techniques and defect/damage-arresting methodology will provide structures that will permit safer aircraft with lower life cycle costs because of the need for fewer inspections and repairs. Advanced structures for the propulsion system will evolve through the development of tougher, more durable materials. High-speed propellers will significantly reduce fuel consumption. New rotor concepts and advanced transmissions for rotorcraft will permit much greater lifting capability and lengthened fatigue life. Advanced structural concepts, resulting in aircraft configurations much different from those we know today, will provide the ability to produce aircraft having lower weight and cost and reduced maintenance requirements. Advanced structures analysis capability using large-scale computing techniques will reduce development and testing costs and time.

Specific resulting improvements could include

- wings capable of adapting their shape, conformally through continuous chordwise and spanwise variations, to maximize specific performance factors;

- aerothermal structures with low weight and adequate life capable of operating in the thermal environment of future high-speed aircraft and cruise missiles;

- damage tolerant structures capable of performing a mission with various types of inherent or induced faults; and

- propulsion system structures that will be 25 percent more efficient and 50 percent less costly to design, and that will have a 50 percent increase in thrust-to-weight ratio and 100 percent increase in life.

Materials

Materials development and advances in related manufacturing technology will play a key role in aircraft systems of the year 2000. Among the materials developments projected for the year 2000 are new composites and alloys for structural members; superalloys; ceramics and glass composites for propulsion systems; and carbon-carbon composites for high temperature applications where hot strength and ablative resistance are critical, such as the leading edges of reentry vehicles and missiles. These materials of the year 2000 will provide aviation system components having increased strength, lower weight, improved toughness, longer life, higher use temperature, and lower cost.

Specific resulting improvements could include

- o aluminum powder systems offering 20 to 40 percent better strength-toughness-corrosion resistance;

- o advanced composites, particularly those utilizing carbon fiber reinforcements, replacing aluminum as primary material in aircraft;

- o development of metal matrix and graphite or carbon-based composites allowing significant improvement in aircraft effectiveness and costs, i.e., higher temperature capability (to 1000°F); fabrication techniques to produce high quality; less expensive parts; and the ability to tailor properties and improved quality assurance;

- o high strength/temperature tolerant materials (ceramic coatings, glass-ceramic, carbon-carbon, etc.) allowing gas turbine engines to operate at higher rotor speeds, temperatures, and pressure ratios;

- o materials for subsystems permitting, for instance, better quality measurements (fiber optic sensors), lightweight fiber optic communication systems, and fire resistant interiors; and

- o computational capability to calculate materials properties behavior from first principles, allowing rapid preliminary evaluation of new materials concepts.

Guidance, Navigation and Control

Guidance, navigation, and control (GNC) historically have been vital to the success of any aircraft. During the next 20 years, GNC systems will move from a supporting technology to become a dominant feature of integrated aircraft design. Factors that are projected to contribute to this role of GNC systems in aircraft of the year 2000 include dramatic increases in onboard computing capability, improved ability to collect and process massive amounts of information from multiple sources, development of dependable onboard digital/electronic systems for mission and life critical functions, improved understanding and use of the controls as a means of relaxing classical airplane design constraints, and development and use of systems to integrate traditionally independent functions in the design phase for performance benefit. These advancements are projected to result in complete integration of aerodynamic, propulsion, and structural controls to provide aircraft with dramatically increased performance, new capabilities, and improved mission effectiveness.

Specific technology advances projected for the year 2000 are

- o multidisciplinary design capability for highly interactive aircraft subsystem controls which would allow optimization of speed, range, maneuverability, efficiency, observability, and mission effectiveness through relaxation of classical design constraints;

- active subsystem controls using direct measurement of critical performance parameters such as airflow, clearances, loads, and temperature for more exacting control of engines, or distributed controls for aircraft geometry shaping that could result in direct, local flow control over major portions of the aircraft for cruise efficiency or maneuvering enhancements;

- automated situational information management systems that could blend and display information on navigation, terrain, obstacles, threat, air traffic, and vehicle status in order to generate trajectories or options for optimal mission effectiveness;

- optimal allocation of man-machine roles and tasks in the design stage that could enhance overall mission success and minimize human error or its effects;

- ultra-fault-tolerant active control systems with on-line configuration capability to provide dependable operation under normal and adverse conditions;

- advances in software technology that would permit significant reductions in development costs of complex software and enhance testability of complex systems;

- massive onboard data bases that could aid the pilot and crew in mission conduct, tactics, and vehicle system management;

- new classes of sensors for guidance, navigation, and control that could allow the implementation of "microcontrol systems" to permit dramatic extension of current aircraft mission capability and allow more freedom in configuration selection; and

- new classes of actuators and power systems that could support massively distributed controls.

Computer and Information Technology

Information processing technology has been advancing by a factor of 10 every 5 years for the past 35 years and is expected to continue to do so.

The benefits of computers are realized, usually indirectly, through application in disciplines such as aerodynamics; guidance, navigation, and control; and others. Thus, the computer's impact on aerospace technology will be in direct proportion to the extent to which these disciplines exploit advancements in computing technology.

Specific resulting improvements could include

- components that are more than 100 times more cost-effective and of smaller size than those available today;
- ground-based supercomputers composed of up to 100,000 processing elements, containing up to 10 Gwords of RAM, capable of executing at rates up to 1,000 GFLOPS, and operating with essentially no unscheduled maintenance;
- airborne systems containing processors with speeds up to 1,000 MIPS and 50 MWords of RAM each;
- fiber-optics buses and channels for airborne applications with 25 to 50 Gbit/per second capacity on a single optic fiber;
- processors and memory integrated with sensors and effectors for airborne applications;
- workstations containing displays capable of up to 8K x 8K pixel resolution and local processing of 100 to 1,000 MIPS on 32-bit operands with 50 MWords of RAM and rotating storage of 10 to 100 Gwords; and
- software that will support multidisciplinary design and manufacturing tools; distributed, heterogeneous data bases; and system verification and validation.

Some specific impacts of information processing technology could include

- dramatic reduction in length of the product development cycle through use of wideband communications to speed the flow of documentation;
- high-performance design centers to provide significant leverage in aeronautics modeling and simulation, design, and optimization;
- significantly better man-machine interfaces to improve the safety and efficiency of aircraft operation;
- total flight management systems, including aircraft state monitoring, navigation, automatic guidance and flight optimal control, dynamic control of structure stiffness, and maintenance;
- significantly better communication among aircraft systems and between aircraft and ground-based systems;
- pilotless aircraft for communication relays, survey and reconnaissance (such as fire control), cargo hauling, and other

military applications such as defense suppression; these aircraft will be either totally autonomous or a combination of autonomous and remotely piloted; and

- o imaging systems for use in applications such as terrain/map correlation, collision avoidance, and landing aids.

Human Factors

The principal focus of this panel was on research issues associated with civil transport aircraft design and operation in the year 2000 and beyond. However, most of the principles and issues addressed were generic in nature and, thus, can be considered generally applicable to other classes of aircraft and missions. Further information on specific human factors research issues related to the unique requirements of military aircraft is contained in recent reports on this subject cited in the bibliography.

Economic incentives, the desire for enhanced safety and reliability, and advances in the art and science of systems integration will result in increased acceptance and use of automation in the cockpit and in ground-based systems in the year 2000.

Major developments projected by the year 2000 in human engineering include human error tolerant systems, adaptive aiding and dynamic task allocation systems, the interaction of artificial and natural intelligence, and an integrated system design methodology.

The very great increase in the quantity and quality of real-time information available to operators on the ground and in the air together with the automation of most basic flight and system control tasks is beginning to alter significantly the role of the human operator in aircraft systems. In most present-generation civil transport aircraft, a substantial proportion of the pilot's task is concerned with basic flight path management and the operation of aircraft systems. In aircraft of the future, it is anticipated that virtually no manual control tasks will be performed routinely by the pilot, and the principal activities of the crew will be to perform cognitive mission management tasks, i.e., the acquisition, processing, and manipulation of symbolic information required to accomplish the mission. The unique capability of humans to assimilate and process data and make decisions in the face of uncertainty and ambiguity, especially when dealing with unexpected or "non-nominal" events, makes it likely that human operators will continue to play a critical, central role in aircraft operations for the foreseeable future. At the same time, human limitations in dealing with the rapidly expanding volume of data must be recognized as an increasingly inportant issue.

Specific resulting improvements could include

- o human error tolerant systems allowing humans to detect errors quickly and respond flexibly without inordinate constraints;
- o use of adapative aiding and dynamic task allocation capability to determine on-line the best information processor (computer or human);
- o artificial and natural intelligence interaction to produce optimum mix and to answer the "who is in charge" question; and
- o integrated system design methodology developments to permit the human factors of design, operations, maintenance, and management to be used in a more efficient and effective manner.

Systems Integration

As noted earlier, the Systems Integration Panel reviewed the state of knowledge projected for the year 2000 by each technology panel, then conceptualized vehicle types that could be derived from these projected advancements in aeronautical technology. From this synthesis, 10 vehicle types were postulated with accompanying projections of potential capabilities. In general, the increasingly high level of integration of the technology advancements projected to occur over the next 15 to 20 years promises to provide aeronautical engineers with a wide range of design options that will offer opportunities for significant improvement in vehicle safety, performance, and economy. It is further anticipated that the projected technology gains will allow development of advanced aircraft systems that present technology will not support.

It should be noted that the panel's forecast of advanced vehicle concepts and capabilities recognizes that it is not likely that each of the pertinent technology advancements will become available for application in the same time frame. For that reason, the projected estimates of performance gains generally may tend to be less than might be extrapolated from the advances projected for each technology and the probability of successful implementation.

Ten vehicle types were selected initially by the Systems Integration Panel because they appeared best suited to bring together and focus the projections of the panels. The selected vehicle types are grouped according to the speed range in which they would operate; they include subsonic, supersonic, hypersonic, and orbital velocity.

The 10 vehicle types are:

- o rotorcraft/vertical takeoff and landing (VTOL) vehicles having significant improvements in speed and range (cruise speeds of 400

knots), reduced operating costs (30 percent lower airframe weight and 40 percent reduction in fuel) and more reliable performance under all weather conditions.

- o long haul airlifter with range of 10,000 miles and range-payload trade-off capability twice that of the C-5A with only one-third more weight;

- o advanced assault transport having terrain avoidance/threat avoidance capability as well as ability to land vertically or in a short distance for troop deployment and removal; capable of deployment on a 24-hour per day basis under all weather conditions;

- o extremely high altitude unmanned aircraft capable of flight above 80,000 feet at low speed (less than 300 knots) with flight time of seven days or more;

- o subsonic transport having 20 to 30 percent improvement over present aircraft in overall operating efficiency with the ability to overcome personnel error failures;

- o advanced fighter aircraft having supersonic cruise and maneuver capability at Mach 3.5, operational altitude in excess of 70,000 feet, maneuver capability at cruise Mach number in excess of 2 gs and a "zoom climb" capability to over 100,000 feet;

- o supersonic transport with capabilities greater than those of the Concorde in payload, range and speed, and that meet every legal requirement (e.g., noise, pollution) and are wholly competitive with subsonic airplanes in terms of airplane cost and fare structure while reducing trip time by one half;

- o attack aircraft having both a supersonic (Mach 2) flight speed and short takeoff-vertical landing capability and a 24-hour a day operational capability under all weather conditions;

- o hypersonic systems (aircraft and missiles) having 2 to 3 times the standoff range of current systems as well as quick reaction capability and significantly increased speed;

- o transatmospheric vehicles having far greater operational flexibility and performance capabilities than the present space shuttle; it would have a high lift-to-drag ratio (approximately 3.0 at reentry velocities) and the capability to operate at a radius of action of 10,000 miles (global coverage) and return to the United States in 2 hours; it would be rocket powered initially, but an airbreathing propulsion system is considered feasible in the longer term.

These examples of air vehicle concepts represent the product of the Systems Integration Panel working in parallel with the technology panels during and immediately after the workshop. This list of projected vehicle concepts provided a starting point for a follow-on activity by an ad hoc Panel on Vehicle Applications, which was created by the Aeronautics and Space Engineering Board subsequent to the workshop to review and analyze in greater depth these and other advanced vehicle concepts based on the technology projections of the workshop.

Further details and more complete description of the findings of the seven technology panels and the Systems Integration Panel are given in the following individual reports of those panels.

Report of the Panel on Aerodynamics

Richard G. Bradley, Panel Leader
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15.

AERODYNAMICS

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AERODYNAMICS

Introduction

Progress in aerodynamics over the past 50 years has been evidenced by the development of increasingly sophisticated and efficient flight vehicles throughout the flight spectrum. Advances have generally arisen in an evolutionary manner from experience gained in wind tunnel testing, flight testing, and improvements in analytical and computational capabilities. As a result of this evolutionary development, both military and commercial vehicles operate at a relatively high efficiency level. This observation plus the fact that airplanes have not changed appreciably in outward appearance over recent years has led some skeptics to conclude incorrectly that aerodymamics is a mature technology, with little to be gained from further developments in the field.

It is of interest to note that progress in aerodynamics has occurred without a thorough understanding of the fundamental physics of flow, turbulence, vortex dynamics, and separated flow, for example. The present understanding of transition, turbulence, and boundary layer separation is actually very limited. However, these fundamental flow phenomena provide the key to reducing the viscous drag of aircraft. Drag reduction provides the greatest potential for increased flight efficiency from the standpoint of both saving energy and maximizing performance. Recent advances have led to innovative concepts for reducing turbulent friction drag by modifying the turbulent structure within the boundary layer. Further advances in this basic area should lead to methods for reducing skin friction drag significantly.

The current challenges for military aircraft open entirely new fields of investigation for the aerodynamicist. The ability through very high speed information processing technology to totally integrate the flight and propulsion controls can permit an aircraft to fly with "complete abandon," avoiding departure, buffet, and other undesirable characteristics. To utilize these new control concepts, complex aerodynamic phenomena will have to be understood, predicted, and controlled.

Current requirements for military aircraft include configuration optimization through a widened envelope from subsonic to supersonic and from low to high angles of attack. This task is further complicated by requirements for control of observables. These challenging new designs do not have the luxury of a large experimental data base from which to optimize for various parameter combinations. Consequently, there exists a strong need for better techniques, both experimental and computational, to permit design optimization in a complete sense.

Enhanced integration of the propulsion system with the airframe offers the potential for very large performance improvements in future aircraft. This can be accomplished with novel thrust management approaches, such as thrust vectoring for control, powered lift, and thrust reversing. Other possibilities include unique propulsion aerodynamic concepts such as high-speed turboprops and supersonic through-flow fans.

The current status of rotorcraft design methodology is analogous to that of fixed-wing aircraft in the early 1970s and is thus rife with possibilities for improvements. To make improvements in speed, range, noise reduction, and reliability of rotorcraft will require the exploitation of the enabling technologies of computational fluid dynamics, fundamental flow physics, and modern diagnostics.

Enabling Technologies

A full understanding of some of the basic flow mechanisms and the capability to accurately compute or measure complex flow characteristics have presented a major stumbling block for air vehicle designers. Marked improvements in these basic areas are needed to fully exploit the potential gains in aerodynamics.

Computational Fluid Dynamics

Computational fluid dynamics (CFD) is an enabling technology that has become an essential tool in a wide range of aeronautical analysis and design applications. CFD provides analytical techniques to expand the understanding of fundamental flow physics as well as to provide easy-to-use, synergistic design and analysis methods of increasing complexity and completeness.

Status For subsonic flow, lift, induced drag, and pressure distributions can be computed over highly complex geometric configurations using the linearized inviscid equations. Similarly, for supersonic attached flow, the lift and wave drag around slender configurations can be predicted for small angles of attack. This level of approximation is mature and widely used. Using the nonlinear inviscid equations set, all of the above computations can be carried out without the slender body restriction. With the additional coupling to a boundary layer analysis, skin friction drag for some simple geometries and improved pressure distributions can be computed.

The use of Reynolds-averaged Navier-Stokes equations requires that the turbulent momentum and energy transport for all scales of turbulence be modeled. This equation set allows computations of separated flows, larger angles of attack, airframe/propulsion interactions, and

some unsteady flows. The accuracy of these computations depends strongly on the turbulence models chosen, which is often a limiting factor.

The large-eddy simulation approximation allows computations of aerodynamic noise, separated flows at large angles of attack, and turbulence intensities. Only the small scales of turbulence are modeled in this approximation. Large-eddy simulations are currently in the early pioneering research phase and are severely limited by available computer power.

The full Navier-Stokes equation set requires no approximations and allows computation of transition, surface pressure fluctuations, and large, unsteady, separated flows. The use of the complete Navier-Stokes equation set is clearly paced by computer development because of the overwhelming memory and speed requirements for even the simplest flow situation.

Projections Computational fluid dynamics will continue to advance at an accelerated rate, paced by the explosive improvements in computer hardware. As this available computer power is increased, the modeling of increasingly complex flows will be possible. To take advantage of the capability, flow models and numerical algorithms must be developed in close concert with detailed experimentation to verify the accurate modeling of the physical phenomena. The close coupling of CFD with physical experimentation can enhance the understanding of basic physical phenomena, such as transition and turbulence, that have eluded the aerodynamicist for years, while at the same time, developing a verified analysis capability of paramount importance to the designer.

The payoff of CFD to the aircraft designer will be tremendous in that the aerodynamic design of future aircraft systems can be accomplished with greater efficiency and confidence. Development of this capability must be approached by defining algorithms and solution grid generators for complex geometries. The overall goal in computational fluid dynamics is to reduce aerodynamic design and analysis costs by at least 50 percent and, at the same time, to achieve a better configuration.

Wind tunnels and CFD, when combined interactively with experimental studies, will provide the capability to obtain near real-time data analysis. In most situations, numerical simulation of the experiment will define how it should be conducted, as well as critical measurements to be made. The real-time coupling of the experimental boundary conditions with flow simulations will allow on-line extrapolation of wind tunnel results to true flight conditions and/or correction of wind tunnel test data to eliminate wall, support, and instrumentation interference effects. The outcome will be at least a 50 percent

decrease in the time and cost required for obtaining critical physical data and verifying computational codes/designs.

In several situations, critical technology is not amenable to direct physical testing due to cost, extremes of environmental test conditions, or personnel/facility safety restrictions. As CFD capability increases, numerical studies will be used even more in flow regions where experimental testing is not feasible or economically justifiable. CFD will provide performance predictions for vehicles at the extremes of the flight envelope without risk to human life and expensive developmental aircraft or spacecraft. Two immediate areas to benefit will be low-density, high-energy flows typical of upper atmosphere maneuvers by transatmospheric vehicles or orbital transfer spacecraft, and high-density, high-energy flows typical of hypervelocity planetary entries/reentries.

The techniques of flow visualization are progressing rapidly and, by the end of this century, truly revolutionary advances may be at hand. One such desired development is the real-time flow visualization from computer flow simulations using projected holograms. This offers the exciting possibility of being able to "walk around" an aircraft or inside an engine with flow simulation to a particular flight condition. This would allow "close-up" examination of local flows, turbulence, separation, and propulsion system flow interaction.

Fundamental Flow Physics

Significant progress in applied aerodynamics is dependent upon the fundamental understanding of the mechanisms critical to the prediction and control of turbulence, transition, separation, and vortex dynamics, of complex aerodynamic flows over air vehicles throughout the speed range from hover to hypersonic.

Status The fundamental physics of 3-D steady and unsteady viscous flows, such as turbulence, transition, separation, and vortex dynamics is not fully known. The relationships between flow structure and acoustic sources are not sufficiently understood. Presently, however, it appears that the control of acoustic emissions depends strongly upon the management of turbulent shear flows. Empiricism has been and continues to be the mainstay of design. Rapid developments in computation capability are the basis for most of the analytical accuracy that is presently achieved. At the same time, unobtrusive instrumentation techniques have opened up new avenues of experimental research using small, economical wind tunnels.

Following are the consequences of this situation that affect the progress of significant advances in aeronautical technology:

- The optimization and control of such flows are contingent to a large extent on increased understanding,

- The anticipated growth of CFD is limited by a dearth of advanced experimental benchmarks and basic physical modeling, and

- Large excursions in the design of future vehicles from the present norm will not be able to rely on existing empirical data; extrapolation of the present data base requires increased cognizance of the fundamentals.

Projections Major advances in the fundamental understanding of complex, viscous flows will be achieved by taking advantage of the advances in computational and experimental capability. Achievable goals for the next 15 years include a usable model for transition and turbulence structure; an understanding and modeling of parameters governing 3-D separation and reattachment; and an understanding of vortex formation, vortex interactions, and vortex breakdown phenomena. These advances will require a coordinated and integrated research program to be carried out with major participation by universities, government laboratories, and industry. In addition, maximum utilization and development of advanced computational methods and instrumentation are necessary. Some approaches are outlined below.

Computational approaches:

- development and utilization of advanced codes (e.g., large-eddy simulations) to conduct "numerical experiments" for detailed insight into 3-D steady and unsteady viscous flows;

- application of direct numerical Navier-Stokes simulations for optimization of active and passive turbulence and vortex control concepts and to increase understanding; and

- development of numerical holograms of flow fields for microscopic observation and comparison with measured data.

Experimental approaches:

As an adjunct to and validation of the numerical experiments, instrumentation and facilities capable of making simultaneous three-dimensional measurements in unsteady viscous flows should be developed. Examples are

- holographic anemometer with a high-speed capability of at least 1,000 holograms per second;

- three-component scanning laser doppler anemometer to obtain almost instantaneous profiles;

- o resonant doppler anemometer;
- o pulsed-wire technology for an active separation-control sensor;
- o "black-bubble" visualization in water (This is a technique for visualizing flows and represents an advancement over current hydrogen bubble techniques.);
- o digital image processing as a quantitative measurement tool; and
- o specialized facilities for unsteady flows.

Using the numerical and physical tools described above, details of turbulence, separation, transition, and vortex dynamics can be explored. Specific areas of concern are highlighted.

Drag Reduction

The classic problem for aerodynamicists has been the reduction of overall drag for flight vehicles of all types. Several evolving concepts and better understanding of the fluid flow fundamentals will lead to significant improvement in configuration drag characteristics. The goal is to reduce configuration net drag for purposes of increased range, increased speed, decreased size (weight and volume), decreased fuel usage, greater acceleration, and/or enhanced maneuverability. The following paragraphs examine the basic drag elements in light of potential gains for the future.

Viscous Drag

Laminar Flow Control

Status An extensive theoretical and experimental data base exists, primarily from the 1950s and 1960s and recently updated by NASA under its aircraft energy efficiency program (ACEE), which indicates that, with sufficient care, laminar flow can be obtained up to Reynolds numbers of approximately 60×10^6. Laminar flow control (LFC) suction is not currently utilized because of residual questions concerning cost, maintainability, and reliability of active LFC systems. Pressure-gradient-stabilized (passive) control is currently achieved for low-speed aircraft (general aviation) and is undergoing further development.

Projections Considerable time and effort have been expended in the past in quest of a successful LFC system. Although these efforts have produced disappointing results, the fact remains that the potential payoff for successful implementation of LFC is large. Reductions of wing skin friction drag by 80 percent and overall subsonic aircraft of

25 percent are possible with combined active and passive control concepts. Successful achievement of laminar flow in supersonic flow can provide similar drag reductions, up to 30 percent in total drag, plus significantly reduced surface equilibrium skin temperature (160° reduction at Mach 3.5). Suggested approaches include

- o continued research on maintenance and reliability issues for suction LFC (primarily on wing/nacelle/empennage surfaces) including (1) definition of disturbance parameter space (including combined influences); (2) continuation of in-flight maintenance and reliability experiments; and (3) definition of options and consequences for loss of laminar flow in-flight, including possibility of "fail safe" systems to reestablish the laminar condition;

- o determination of system feasibility of in-flight "active" (feedback) control of laminar instabilities, including development of appropriate sensors, actuators, and associated logic circuitry;

- o optimization of passive LFC techniques, including pressure gradient, wall temperature control (cooling or perhaps distributed heating), and combined suction/injection using passive bleed; and

- o completion of development of LFC techniques for supersonic flow with an assessment of additional payoff through reduction in radiation equilibrium surface temperature.

Turbulent Friction Drag

Status Recent turbulent drag reduction inventions (late 1970s) utilizing passive nonplanar wall geometry indicate turbulent skin friction drag reductions of up to 20 percent are possible for fuselages. The available data base is restricted to low speeds. Of particular interest is that many of these devices can be retrofitted into existing aircraft/missiles.

Projections Continued development of turbulent flow control and turbulence modification devices can lead to significant reduction in turbulent friction drag. Reductions of as much as 25 to 30 percent in fuselage C_f is projected for subsonic flow and 10 to 15 percent at supersonic Mach. The lack of understanding of fundamental turbulent flow phenomena has been a major handicap in reducing the friction drag of flight vehicles. Future advances in CFD will provide the needed capability to complement the experimentally based concepts that are given in the following suggested approaches:

- o continued development and optimization of various devices for operation at increasing speed, dynamic pressure, and Reynolds number;

- o utilization of the turbulence structure sensitivity information gathered in this research to provide new insight for turbulence modeling for attached boundary layers;

- o determination of feasibility of utilizing sensors, actuators, and associated logic circuitry to actively control turbulent boundary layer dynamics ("smart walls"); and

- o investigation of pressure-gradient-induced skin friction reduction in conjunction with active or passive control techniques for acceptable off-design performance.

Wave Drag

Status An extensive body of thin wing and slender body data exists. Emphasis has been placed on blending and variable sweep applications to optimize configurations across a Mach number range. In contrast to supersonic transport design, present fighter configurations have wave drag levels that significantly exceed their corresponding body-of-revolution, linear theory optimums. In fact, these optimum shapes provide a theoretical lower bound of wave drag that is 60 to 70 percent below the level of current fighters.

Projections Continued applications of configuration blending, flow control, and wave cancellation techniques can lead to reduction of up to 40 percent in wave drag for fighter configurations at supersonic cruise. Some possible areas for investigation include

- o reexamination of wave cancellation schemes using viscous flow control techniques to help attenuate shock/surface interaction effects; consideration of ring wing, joined wing, and wave rider concepts; and

- o optimization of configuration supersonic fineness ratio with variable geometry and increased fuselage loading to reduce supersonic wave drag due to lift.

Drag Due to Lift

Status Drag due to lift is critically related to wing aspect ratio and to the ability to maintain attached flow over the design lift range. Structural considerations set the limit for simply increasing span to reduce drag due to lift. Winglets have been used to enhance effective span and span-loading effects. Attempts to reduce the drag associated with shock-induced separation have led to shockless or weak shock airfoil designs.

Projections It is possible to tailor wing planform and structural arrangements to achieve improvements of 30 to 40 percent in drag due to lift for specific applications. Suggested approaches include

- o exploration of strut-braced wings, ring wings, joined wings, or joined wing tail to obtain higher aspect ratio;
- o optimization of tip modifications such as winglets, outboard nacelles, tip spanwise blowing to increase effective aspect ratio;
- o development of aeroelastically tailored wings to optimize camber and twist as a function of lift; and
- o integration of vortex generating surfaces to control separation in the high lift range; further vortex control potential is given in a subsequent subsection.

Interference Drag

Status Juncture design is currently a cut-and-try operation. Inlet boundary layer diverters are located to avoid ingestion of outer fluctuating boundary layer vorticity into compressor face. Improvements can be made in both cases to provide additional drag reduction. Progress has been made in reducing stores carriage drag by taking advantage of favorable interference.

Projections Careful attention to local interference mechanisms can produce large improvements in the drag associated with component junctures, boundary layer diverters, and store carriage drag. A savings of 60 to 70 percent in weapons carriage drag is possible compared to conventional pylon/rack carriage. Some potential approaches are

- o refining the use of continuous second derivatives (curvature) in three dimensions on surfaces to diminish juncture interference;
- o utilization of large-eddy breakup devices to reduce extent of outer fluctuating vorticity region in turbulent boundary layers to allow reduction in size of boundary layer diverters; and
- o optimization of conformal carriage for reduction in store/weapons carriage drag by exploiting favorable interference on both stores and aircraft components.

Rotorcraft Hub and Fuselage Drag

Status Many existing rotorcraft fuselages are designed with little priority given to aerodynamic efficiency. Analytical design procedures are limited to simple potential flow codes combined with 2-D or 3-D boundary layer calculations with separation criteria and simple prespecified rotor and fuselage wakes.

Projections Optimized fuselage and hub designs will provide significant improvements in helicopter speed and range. A reduction in fuselage drag of as much as 60 percent is believed to be possible with improved analysis capability. A suggested approach is

- o use of advanced computational methods to compute the flow about rotorcraft fuselages, including the influence of the rotor wake (i.e., the geometry of the wake; the nature of the vorticity in the wake; and the effect of that vorticity on blades, fuselage, and tail); and

- o optimization of rotorcraft fuselages with negligible separation at design conditions, and improvement of tail rotor/empennage designs utilizing computational design procedures.

Aero/Propulsion Integration

Configurations have traditionally been designed with the aerodynamic/airframe and engine/propulsion system primarily treated as individual but complementary elements. Deliberate efforts are made to improve the interface and interactive components for closely coupled configurations, or when it becomes apparent that strong interactions demand such. The coupling of the aerodynamic and propulsive technologies to assure synergism in the design will increase with the use of thrust vectoring, in-flight thrust reversing for combat aircraft, and propulsive lift. Also, propulsion aerodynamic concepts, such as high-speed turboprops and supersonic through-flow fans, offer the potential for large improvements in engine efficiency and performance.

Inlets

Status Inlets can currently be designed to achieve acceptable levels of total pressure recovery, flow distortion, and aerodymamic drag. Supersonic inlets are generally limited to operation under Mach 3.5. They normally incorporate variable geometry compression ramps and fairly simple boundary layer bleed systems to maintain high pressure recovery and low flow distortion over the range of operational Mach numbers. Limited variable inlet capture area has been employed, but primarily to provide improved pressure recovery and distortion in maneuvering flight. Since internal pressures are very high at supersonic Mach numbers, the structural weight of the typical long-diffuser inlet tends to be rather high.

New inlet shapes are being developed, but the expense of testing a broad array of configurations in wind tunnels inhibits assessment. Limited work has been done to determine the importance of geometric design and airframe-inlet integration on the total aircraft drag.

Some work also has been conducted relative to top-mounted inlet flow fields, innovative inlet aperture design, and subsonic diffuser design relative to increasing the survivability aspects of the integrated designs.

Projections In general, the goal in inlet design is to make the inlet-engine system insensitive to flight conditions. Advances are possible with innovative variable capture systems using sophisticated boundary layer control systems. These inlets will be developed to operate efficiently from subsonic speeds to Mach 6.0. To achieve rapid acceleration, variable capture inlets and flexible mixed compression inlets will be developed to minimize spillage drag and maximize pressure recovery throughout the Mach/maneuver envelope. Tailored bleed systems and/or advanced blowing systems will be used to maintain acceptable flow quality. In order to reduce inlet weight, much more compact inlets will be developed that are substantially shorter and lighter with length-to-diameter ratios of 2 or less.

Integration of the inlet into the aircraft will be optimized for drag spillage and interference effects. The link of reduced observables with high internal performance and reduced drag will be established for a wide variety of subsonic and supersonic advanced inlets. Both the inlet location and its design will substantially influence performance and survivability. Top-mounted, conformal, semisubmerged, and flush inlets will be analytically and experimentally assessed, and the data base will be available for design of subsonic and low supersonic aircraft. At very high speeds, active inlet system integration employing sensitive variable geometry inlet systems will enable optimum efficiency to Mach numbers of 6.0. Prediction techniques that are able to discriminate differences in drag, pressure recovery, and even flow distortion among various inlet designs will be developed to enable establishment of design criteria for performance and survivability.

Nozzles

Status A large date base exists for axisymmetric nozzles, and the data base is now starting to grow for nonaxisymmetric, or 2-D nozzles. Nonaxisymmetric nozzles have been investigated to determine their relative advantages and disadvantages and are being considered as strong candidates for improved integration of thrust reversing and thrust vectoring in advanced aircraft. Low-to-moderate aspect ratio nozzles (aspect ratio 4 to 7) have been investigated with good success.

Nonaxisymmetric nozzles have shown some advantages for several types of tactical and strategic missions, but are not expected to demonstrate a universal advantage over postulated axisymmetric installations. Aerodynamic installation design for high-performance nozzles has focused on achieving reduced transonic drag and reduced

complexity. Nozzle designs are also being formulated that can function effectively for improved short takeoff and landing (STOL) aircraft maneuverability, and survivability. Concentration has been primarily on the aerodynamic performance; however, the impact on survivability levels is being developed.

Projections Higher aspect ratio, nonaxisymmetric nozzles will be possible, with nozzle throat aspect ratios approaching 20. The aerodynamic design criteria and 3-D computational methodology for low drag will be quantified for efficient supersonic cruise capabilities. The data base will be developed numerically and experimentally to compare nonaxisymmetric and axisymmetric exhaust nozzle flow fields and their influence on afterbody nozzle drag; this could possibly provide as much as a 50 percent reduction of nozzle drag. Data generated will be employed for development of aerodynamic design criteria and improvement in computational procedures. Design criteria for greater reduced radar cross section and all-aspect infrared signature will be established.

Multifunctional nozzles will be developed that will reduce drag levels over a wide range of Mach numbers. Development of new concepts that can operate effectively at supersonic Mach numbers in dry power will result in significant increases in cruise performance. The development of new nozzle designs will be enhanced by the application of sophisticated numerical techniques. Accurate calculation of the boundary layer separation tendencies by these advanced CFD codes will pave the way for new nozzle installation designs. The capability of the advanced nozzle to take the place of control surfaces also will be developed and will allow trim and maneuvering capability. Vectored nozzle technology could very well lead to a high-performance VTOL fighter with no standard aerodynamic controls and, therefore, with only a very small penalty for vertical flight regime capabilities.

Thrust Reversing/Thrust Vectoring

Status A technical data base has been established for incorporation of thrust reversing and thrust vectoring (TR/TV) capability into nonaxisymmetric nozzles. The base includes data on internal and external performance, cooling, and broad levels of survivability. Ground demonstration of a V/STOL-type nozzle of the single expansion ramp class has been demonstrated on a current turbojet engine. The demonstrations were successful with good performance levels indicated. Concentration has been on 2-D nozzle thrust reverser installations, although additional work is now proceeding with axisymmetric nozzles. Instantaneous and sustained maneuvers have been and are being evaluated and compared. Recent work has been extended to the STOL area combining sophisticated aerodynamics with the multifunction nozzle.

Projections Afterbody-nozzle designs specifically for STOL (along with operating versatility and survivability) will be possible. The use of TR/TV nozzles will enhance both instantaneous and sustained maneuverability. The TR/TV nozzles will also permit required fuselage pointing during combat for weapon delivery. The STOL performance provided by TR/TV capability in the exhaust system will provide substantial basing flexibility. The use of the nozzle for control to replace control surfaces for trim and maneuver will be possible. Also, large reductions in takeoff and landing distances are foreseen.

Propulsive Lift

Status Many methods for propulsive lift have been investigated at different levels of detail. Techniques considered include spanwise blowing, chordwise blowing, jet flaps, tangential boundary layer control, vectored-engine-over-the-wing, upper surface blowing, externally blown flaps, and transverse thrust lift augmentation. Changes in effective camber and supercirculation can be achieved with different levels of blowing momentum. Lift augmentation has been shown to levels of C_L from 3.0 to almost 10, but the high levels have generally not been considered usable.

Projections Techniques will be developed for both spanwise and chordwise blowing. Blowing levels will be reduced to values that will not seriously detract from the engine performance. Bleed air from the compressor will be minimized. Enabling techniques include new engine cycles such as the variable cycle engine. Spanwise-blowing/transverse-thrust lift augmentation will be available for use in design and will generate increases in lift at acceptable blowing rates. The propulsive lift can be used to enhance maneuvering capabilities, as well as to improve takeoff and landing characteristics. Sophisticated techniques, such as power profiles that generate propulsive life and are, in a sense, contributing thrust devices, also will be available to double the usable maximum life and to increase the lift-to-drag ratio by 25 percent, allowing range increases for small, compact aircraft.

Rotor Design

Status Rotor design is currently accomplished using simple blade element theory, coupled with prescribed wakes. Three-dimensional and unsteady effects are estimated from an empirical data base. Development of novel or innovative concepts requires extensive test programs. Acoustic predictions are developed from simplistic acoustic analysis.

To achieve the dual requirements of vertical takeoff and transonic maneuvering forward flight, some approach other than conventional helicopter rotors must be developed. One approach that appears to

hold promise is the circulation control rotor that locks for forward flight. The development of circulation control rotors is at an early stage with only one marginally successful flight demonstration. Empirical design procedures are used for airfoil geometry, and 3-D and unsteady effects are largely unknown.

Projections Time-dependent Navier-Stokes codes will be used and coupled with hybrid modeling of rotor wakes to optimize rotor designs. Analytical studies will be complemented with detailed experiments incorporating unobtrusive diagnostics. Viscous flow control will be used to optimize rotor performance. Aerodynamic design methods will be coupled with advanced acoustic prediction techniques to optimize rotor designs for high performance and low noise. Rotors having noise levels within Federal Aviation Administration standards, 50 percent lower vibratory loads, and 20 percent more L/D or less required hub torque will be available. Integration of the rotor and fuselage aerodynamics will provide low net drag rotorcraft.

Detailed, ground-based experiments that incorporate advanced unobtrusive diagnostics and flight experiments will be conducted to optimize circulation control rotors and wings. This approach in a stopped rotor concept can result in rotorcraft that are capable of transonic maneuvering flight, with the vertical lift efficiency of a helicopter. Potential expansion of the stopped rotor concept to transonic speeds and reductions in rotor complexity is possible.

Aerodynamic and Propulsive Force Blending and Control

Status This area has largely been focused on missiles and high-speed vehicles at high altitudes. Complete aerodynamic control as well as complete propulsion control have been investigated, but only limited studies are available for force management blending and consequent interactions. Trade-offs in terms of aerodynamic and performance efficiency and optimization have not been conducted at a level sufficient for use in the design of very high performance missiles and flight vehicles. Further information on control systems is given in the reports of the Panel on Guidance, Navigation and Control (pp. 134-142) and the Panel on Propulsion (pp. 59-60).

Projections The quantification of the performance capability required to enable tactical and strategic air missile design and development will be possible. Specifically, the trades will be identified to enable the management of aerodynamic and propulsive forces. Optimization will be possible to permit slew to 180 degrees, thereby yielding the capability for placing the majority of the offense and defense functions on the missile rather than on the aircraft. Minimization of deleterious aerodynamic disturbances at launch along with the immediate control of the weapon will be possible. Rapid slew

to the target will offer a new capability for the mission or systems analysts. The blending of the aerodynamic and reaction controls also will be possible for high-speed, high-altitude vehicles.

Hypersonic Aerodynamics/Aerodynamic Heating

Status Analytic methods to predict aerodynamics and heat transfer in flight at hypersonic speeds are in a rapid state of development. The availability of high-speed computers makes it possible to apply general flow and body streamline descriptions to arbitrary bodies, including inlet and exhaust effects. Complete Euler solutions arrive at overall streamline shapes that are, on the average, of good quality. Another analysis approach uses the parabolized Navier-Stokes solution to provide high-speed flow field predictions and surface heat transfer. Experimental studies of shock interaction provide an indication of the high heating levels that can be generated, but the data base is limited. Airbreathing propulsion integration is an almost untouched aspect of hypersonic flight. Boundary layer separation and transition are, at best, only approximated by empirical functions developed from sparse data. Real-gas effects have not been properly addressed for many years, but the emerging interest in hypersonic vehicles has focused attention on this neglected problem. Interactions of all types are predicted using empirical relations. A limited data bank exists for shock wave interactions, free vortex interaction, and flow separation reattachment near body and surface discontinuities.

Projections Complex vehicles that conform to the constraints of aerodynamic control, airbreathing propulsion, and manned vehicle safety can be designed with much greater confidence and decreases in costs and design time. Exact numerical techniques will be used, with accuracy demonstrated through extensive comparisons with experimental data. The configuration-induced regions of high heating due to shock or vortex interaction will be minimized by applying multiparameter design techniques as well as design of inlet systems with acceptable levels of performance. These techniques will include finite rate chemistry and surface catalytic effects. Improvements in the understanding of boundary layer transition phenomena within the inlet will significantly improve aero heating predictions. Precise leading-edge shape change analysis and active cooling techniques will both be available for application to high heating situations with attendant low observables. The same technology will permit development of cooled, variable geometry inlets. External burning offers a favorable interaction scheme that may provide lift, propulsion, and control forces for advanced airbreathing or composite propulsion vehicles. Airbreathing propulsion vehicles will be able to capitalize on the new technology developments to place inlets in position for optimum pressure recovery and low distortion. A spectrum of advanced propulsion concepts will be brought to high levels of efficiency, approaching the theoretical limit, and will include rocket and dual propulsion modes as well as strictly airbreathing systems.

Ejector Thrust Augmentation

Status A technical data base has been established based on subscale model tests in laboratories and aircraft ground tests that have demonstrated augmentation ratios of 1.6 uninstalled and substantially reduced levels installed, near 1.2. However, these levels of augmentation ratios are not adequate to achieve vertical takeoff with current technology engines and structural weights. The volume efficiency of current augmentors generally is too high for practical application on operational aircraft.

Projections The development of advanced analytical prediction methods that can accurately model the subsonic and supersonic flow regimes along with the turbulent mixing regions in an interactive approach is vital for improving ejector augmentation ratio. Also, improved methods for boundary layer control will be developed. Extensive subscale model tests, using ejector geometries established by the advanced prediction methods, will be needed and will be developed to achieve large gains. It is estimated that an installed augmentation ratio of 2.0 can be obtained through a vigorous program. This advance will result in a practical "cool footprint" VTOL or STOVL capability for high-performance aircraft.

Turboprops

Status Propeller aerodynamic technology was dormant for the 20-year period from about 1955 to 1975. From 1975 to the present, a propeller research program has been underway at NASA to evaluate the potential of turboprop propulsion in the Mach 0.7 to 0.8 cruise speed regime. Current propeller aero design is based on inviscid lifting line and transonic finite difference analyses with 2-D viscous corrections in combination with extensive model tests. Propeller/airframe integration is primarily based on wind tunnel model tests.

Projections Improvements in propeller aero technology can lead to high-speed turboprops that have a 15 to 30 percent block fuel savings, using advanced single rotation (SR) propellers, comparable to equilent technology turbofans for cruise speeds at Mach 0.8. An additional 8 to 10 percent fuel savings may be possible by recovering the swirl losses from SR systems by using counter rotating (CR) propellers or other swirl recovery devices. Also, effective utilization of the propeller slipstream blowing on the wing should lead to values of lift coefficient in the 4 to 8 range during takeoff. To achieve these benefits, propeller aerodynamic modeling will have to improve, extensive scaled model tests will have to be conducted, and propeller/core engine system tests will have to be conducted and to provide an efficient vehicle of installation drag must be minimized. By about 2000, Reynolds-averaged Navier-Stokes codes for both SR and CR propellers will be available. Initial SR turboprop system tests will

be conducted in existing ground facilities and in flight by 1987. By 1995, large size (9- to 15-foot diameter propeller) advanced SR and CR propeller systems will be ready for testing.

Subsonic Turbofans and Supersonic Fans

Status Turbofan nacelles are currently designed using a combination of analytical codes, empirical methods, and model tests that have evolved over the past 25 years. Aerodynamic design of fans is based on 2-D cascade codes, 3-D transonic analysis, and scale-model tests.

Some initial studies and limited analytical predictions have shown attractive potential benefits for a supersonic through-flow fan with a near zero-length inlet. No verified analytical codes exist to analyze the unique shockfree fan concept; however, the 3-D inviscid Euler codes should have application to this problem.

Projections Improvements in nacelle and fan aerodynamics coupled with a bypass ratio (BPR) increase to about 9 to 13, should lead to about a 7 percent block fuel savings. This benefit would come from a slim, short nacelle with low (laminar or reduced turbulent) drag (4.3 percent fuel savings), and an advanced swept high-BPR fan (2.7 percent savings).

There is a potential 15 percent reduction in block fuel or a 20 percent gain in range when the supersonic fan is applied to a Mach 2.5 cruise aircraft. To verify these potential benefits and to achieve the required shockfree flow in a practical fan design, a combined analytical and experimental program is required.

Vortex Management

The management of the vortex structure over an aircraft is desirable for two basic reasons. First, it can be used to delay or control separation: payoffs include increased lift, decreased drag, and improved handling qualities at high angles of attack. Second, wake vorticity can be reduced or redistributed. In this application, the trailing tip vortices (wake vortices) are attenuated or redistributed to reduce their hazardous effects in airport areas. Payoffs include increased airport productivity through decreased time intervals between landings and takeoffs, and reduction in wake vortex accidents.

Delay and Control of Separation

Status The current methods of generating vortices to delay or control separation include

- blowing spanwise near the hinge line or edge of an aerodynamic surface or blowing tangentially from a forebody;

- use of high-sweep, low-aspect-ratio, and sharp-edged surfaces, i.e., strakes, chines, leading-edge extensions (LEX), or canard ahead of the wing; and

- use of high fineness ratio (greater than 4) and flattened (i.e., nonround) forebodies.

These vortices interact with the boundary layer, energize it, and delay separation. In most applications, the vortex pattern lies outside the boundary layer and interacts in a vortex sweeping action. However, the vortices can be imbedded in the boundary layer, as with conventional vortex generators on wing upper surfaces and aft fuselages.

The rudder effectiveness of a vertical tail can be increased by blowing spanwise aft of the rudder hinge line. The blowing jet at the root creates a vortex that lies aft of the hinge line and helps turn the flow in the direction of the deflected rudder. This approach also has application to flaps to provide increased flap effectiveness.

A blowing spanwise jet located in a convex trough at the wing trailing edge can be used as a nonmovable aileron or flap. The flow deflection is governed by blowing rate and blowing location.

The flow around a configuration at high angles of attack will separate. It is important to control this separation from the forebody and wing root region so that strong vortex filaments trail downstream close to the upper surface of the wing. These strong vortices then delay the upper wing surface separation through a vortex-sweeping action on the boundary layer.

The vortex symmetry on the forebody is controlled by strakes or chines on a round forebody, or by a flat, elliptical nose shape. The LEX or canard can produce a very strong and controlled vortex pattern over the wing.

Trade-off considerations for this vortex management include

- the power required for the active blowing concepts;

- the effect on radar performance of forebody shape with strakes, chines, ellipticity, etc.; and

- the strong pitch-up produced by the chines, strakes, or LEX when portions of the wing do finally stall.

Vortex management is currently achieved largely with the use of fixed surfaces. The potential of variable geometry and oscillating surfaces, adaptively employed, is poorly understood. The experimental data base is fair, consisting of point design water tunnel visualization data (dye streaklines), wind tunnel force data, and very limited flight visual data (usually obtained accidentally by photographs on a humid day). The physical understanding of the flow phenomena is based on correlation of visual and force data.

Projections By the year 2000, the status of understanding should improve in all areas of vortex flow and control. This includes the physical understanding, the theoretical methodology, and CFD necessary to predict and design ways of controlling the vortex pattern for any desired effect.

The advances possible include design of efficient, nonmovable control surfaces that produce the required control forces through "vortex blowing." Considerable experimental and theoretical research is needed to provide the data bases for efficient application at minimum blowing rates.

As a result of these advancements, it will be possible to produce a departure free configuration. Forebody blowing, variable geometry or extendable strakes, chines, LEXs, canards, and oscillating or vibrating surfaces, as well as newer concepts could be used as the controlling mechanisms to adaptively reconfigure the vortex pattern to alter lift, control the aircraft, and to arrest departure. With this capability, the fighter pilot could maneuver with "reckless abandon" without fear of overloading or departing the aircraft. The vortex management mechanisms discussed here could be combined with three-axis thrust vectoring used at low dynamic pressure conditions to provide the necessary control power for departure free maneuvering anywhere in the flight envelope. An important part of this capability is the very high speed information processing that should be available by the year 2000. This technique would provide the real-time electronic capability to reconfigure the vortex patterns.

Critically located vortices for local flow control can be used to improve the performance of aircraft afterbodies and of internal flows. The vortices can be stabilized by a combination of geometry design and low blowing rate. The result will be significant redirection of afterbody drag and efficient short diffusers.

Wake Vortex Minimization

Status Minimization of wake vortices is of first order importance for increased airport productivity. Several methods for vortex attenuation and redistribution exist, but the physics are poorly understood and hence the results cannot be generalized with

confidence. Moreover, the existing methods usually degrade performance significantly.

Projections One of the more fruitful approaches is the redistribution of vorticity in the tip vortex through interaction with "control vortices." Currently, such flow control elements are typically generated by spoilers, but much more efficient generation methods should be developed, such as cambered, deployed landing gear doors. The physics of vortex alteration through interaction with control vortices must be studied, understood, and optimized with the added complication of background (atmospheric) turbulence effects. Adequate control of the shed vortex phenomena can reduce the separation time for airport takeoff and landings by 50 percent.

Configuration Synthesis

The ultimate test for achieving significant gains in aerodynamic efficiency lies in actual blending of potential improvements into real configuration geometries. Previous sections have projected specific areas of technology advancement in drag reduction, airframe/propulsion integration, and vortex management over the full spectrum of flight conditions. These potential improvements must be integrated with the other technologies to satisfy not only the usual requirements of performance, economics, and environment (noise and emissions), but also to reduce observables for the configuration. Reducing the radar cross section and infrared signatures of the vehicle and its propulsion system can drive the configuration into unconventional shapes that challenge the aerodynamicist.

Emerging Vehicle Concepts

Status Today's configuration design relies heavily upon wind tunnel testing and the existing data base, which is extensive for conventional shapes. This data base has only limited use in the emerging environment that emphasizes achievement of stringent low observable objectives. As low observable design becomes a more dominant driver, the requirement for new and innovative analysis and design methods becomes apparent. Further information related to configuration design is given in the report of the Panel on Structures (pp. 75-77).

Projections The design community will have appropriate analysis and design tools in addition to the data base to achieve completely integrated configuration synthesis. Extensive configuration research is required to establish the substantiated data base for new, unconventional vehicle shapes that meets a variety of missions and requirements. Aerodynamic analysis and design methods must be developed to accommodate these future vehicle shapes. The opportunity in CFD will be of significant help.

The designer will continue to be pushed in different directions by the conflicting requirements for performance, economics, environment, and reduced observables. Currently, several of these requirements and design disciplines enter the configuration synthesis off-line; consequently, the necessary trade studies to establish the best design are time-consuming. The new computational capacity available will make possible a multiparameter design program that integrates into one design synthesis program the methods for aerodynamics and installed propulsion, structural design, weights, flight control, observables (RCS, infrared, and acoustic), performance, and life cycle cost. The main advantage of this multiparameter design code is that the designer will be able to explore a large parameter space and conduct all the necessary trades to rapidly find the best configuration.

Projecting CFD advancements and continued development of computer capability, the aerodynamicist will eventually have a computational (digital) wind tunnel available for use. Verified, easy-to-use codes will predict the flow about complete aircraft configurations using the Reynolds-averaged Navier-Stokes equations. CFD will also enable the aerodynamicist to predict the flow about progressively more complicated geometries using the large-eddy simulation approach.

Parallel to the growth of large mainframe computers has been the increase in capability of microprocessors. This growth will continue, resulting in significant computing power incorporated into the aircraft itself. This computing power, when combined with computational codes, sensors, and actuators, will provide the capability for real-time aerodynamic and structural adaptability of the aircraft. The control system, flow control actuators, and sensors can be distributed throughout the skin of the aircraft. This technology, when combined with vortex management mechanisms, will allow the pilot, or in the case of RPVs, the aircraft itself, to select any required sequence of maneuvers. Full integration of all aircraft systems will be accomplished, allowing the aircraft to approach "birdlike" adaptive flight.

Further significant progress in this area might well require a much more thorough understanding of the aerodynamic design process, as well as of the advantages, disadvantages, and limitations of both CFD and experimentation in order that a reasonable "expert system" can be made available to support future designers.

The greatest technological gains usually occur at the boundaries between disciplines. The greatest interdependence between the present subject area, aerodynamics, and other technologies occurs in the aeropropulsion, interactive flight control, and CFD areas. However,

advances in all of the areas treated herein are either contingent upon, or will be augmented by, the rapidly evolving computational and data processing fields.

Hypersonic Vehicle Concepts

Status There is a resurgence of interest in developing vehicles capable of flight throughout the subsonic to hypersonic regimes. Past work has been accomplished with an obviously insufficient data base for the high-Mach regime. Analytical tasks have been strongly based on empiricism and lack the capability to resolve the flow field and heating details needed for complex configurations. Analytic methods are now advancing rapidly.

Projections For the special case of hypersonic vehicles, assisted launch likely will still be required in the form of a launch aircraft, but the hypersonic vehicle will have the potential of safe routine landings on standard runways at the conclusion of its mission. The generation of accurate force and moment characteristics across the complete flight range from free molecule to continuum flow will be generated, based on 3-D flow analyses including real-gas chemical effects. New research in the areas of low-density flight will be required. The use of reaction control for global flight times requires fuel weights that cannot be tolerated. Aerodynamic stability at low density will be achieved as a result of this research.

Manned vehicles using metallic or advanced heat shielding concepts will employ active cooling schemes in backfaced geometries. The requirement for cooling will be accurately known before flight tests begin because of reliable test-extrapolation parameters. Rapid-response heat gages will be used in experiments to expand the data base and reduce test cost and also as part of the onboard active control system. The configuration feature of favorable interference may be used to obtain high lift-to-drag ratio. Aircraft design will be accomplished using rapid interactive computer programs. Accurate detailed analysis of surface pressures and heat flux will eliminate the cost and weight of conservative safety factors in structural analysis.

Aerodynamic heating at hypersonic speeds is important for two reasons. First, the overall heat flux into a configuration must be managed to ensure material integrity and subsystem environment. Second, at a local level it is critical, since a hot spot can weaken, erode, and produce failure of critical components while the remainder of the configuration is capable of satisfactory flight. The local problem is the more difficult and is usually associated with vortex impingement from a forward component, or separation and reattachment in the region of fins and flaps. Experimental research will define the critical flow parameters. A combined theoretical and experimental

program will yield solutions to critical problems by the turn of the century. Active cooling schemes will be advanced from hypothetical concepts to demonstrated reality.

All Weather Operation-Icing

Status Icing research was dormant in the United States for about a 20-year period from the mid-1950s to 1978. Current ice protection systems are designed based on limited analysis and old 2-D empirical correlations. Most large aircraft rely on anti-ice protection systems that use large amounts of engine bleed air; however, future engines (turboprop, etc.) with small cores will not have adequate bleed air. Also, composite materials with their lower thermal conductivity will preclude the use of this system. Because of these technology changes, new, more efficient ice protection concepts are needed. Helicopters and general aviation aircraft particularly need all-weather (icing) capability. Their small size (high collection efficiency), low-altitude operation in the clouds, and low power available for ice protection requires that very light and efficient protection concepts be developed. Also, there are many military missions at the lower altitudes (below 22,000 feet) where icing can be a serious problem. Current icing certification relies on limited component tests and analysis with an emphasis on very expensive flight testing.

Projections Advanced ice protection concepts that rely on ice removal (deicing) rather than not allowing ice to build up (anti-icing) can offer significant weight and power savings. Some of these advanced concepts include electroimpulse and piezo-electric to "knock ice off"; fluid systems using efficient porous bleed; advanced cyclic electrothermal systems; microwaves to create a liquid boundary at the ice/aircraft interface; and possibly boots for new applications like helicopter rotors. Design methodologies will be developed based on improved analysis and empirical correlations for these concepts. Since ice will be allowed to build up on both unprotected components and on protected components (before being deiced), advanced analytical prediction methods will be developed to predict the associated aerodynamic penalties and to develop aircraft component geometries that have minimum buildup. Emerging CFD methods will be utilized to accomplish this by predicting droplet trajectories, impingement regions, ice growths, and the resulting separated flows.

Conclusions

Tables 1-1 through 1-6 present a concise overview of the detailed findings of the Aerodynamics Panel. The charts summarize the current status, projections for the future, specific improvement targets relative to the current state of affairs, and suggested approaches to reach the targets.

Table 1-1 Enabling Technology - Computational Fluid Dynamics

	Status	Projection	Target	Possible Approach
General	• Significant progress in solving inviscid flows with viscous correction for attached flows • Some progress in turbulence modeling for Reynolds-averaged N-S equations • Initial work on full N-S equation solutions	• Hardware and software will be developed to provide solution capability for complex geometries across the angle-of-attack/Mach range	• Complete configuration viscous flow field calculation capability verified by comparison with detailed experimental data • 50% decrease in design and analysis cost	• Continue development of algorithms and grids for solving complex flows • Continue development of turbulence models and full N-S simulation • Verify evolving methods by comparison with experiment
Wind tunnel applications	• No real time coupling of wind tunnel and CFD exists	• Productivity of wind tunnel testing will be amplified by coupling with CFD for near real time data analysis, on-line extrapolation to flight conditions	• 50% decrease in time and cost for obtaining critical physical data	• Couple evolving CFD routines with wind tunnel data acquisition/reduction systems
Hypersonic flow	• Often, critical technology not amenable to direct testing due to cost, extreme environmental conditions	• CFD will provide predictions for flows at the extremes of the flight envelope; low-density, high-energy flow and high-density, high-energy flow	• Tools for design of transatmospheric vehicles in lieu of testing	• Develop flow models for complex interacting radiating flows with candidate heat protection systems
Flow visualization	• Techniques being developed to visualize velocity vectors and streamlines of computed flow fields	• Computed flow fields may be examined graphically including details of turbulence, separation, propulsion interactions, etc.	• Real time visualization of flow field details computed by CFD	• Develop advanced 3-D displays coupled with CFD flow calculations

Note: Targets are relative to current operational systems

Table 1-2 Enabling Technology - Fundamental Flow Physics

	Status	Projection	Target	Possible Approach
General	• Workable understanding does not exist for vortex dynamics, turbulence, 3-D separation, or transition • Empiricism is the mainstay of design • The relationships between flow structure and acoustic sources not sufficiently understood	• Significant advances in the fundamental understanding of these phenomena • Increased understanding essential to permit quantum jumps in aerodynamic design capability	• Usable model for turbulence and transition • Understanding of vortex interactions, formation, & burst phenomena • Establish physics of 3-D separation and reattachment	• Utilize CFD to conduct numerical experiments • Develop instrumentation capable of making unobtrusive 3-D measurements • Combine controlled numerical and physical experiments to validate physical models • Conduct large scale fundamental experiments in separated flows for turbulence model development
Acoustics	• Control of acoustic emissions depends strongly on turbulent shear flow management	• Turbulent B.L. control for drag reduction will result in lower total acoustic emissions	• Fundamental understanding of acoustic generation in 3-D unsteady, viscous flows	• Integrate acoustic emission requirements in the development of active/passive drag reduction devices

Note: Targets are relative to current operational systems

Table 1-3 Drag Reduction

	Status	Projection	Target	Possible Approach
Laminar Flow Control Subsonic	• Extensive data base • System Reliability & maintenance questions unresolved	• Can achieve laminar flow to R_N of 60 x 10^6	• 80% wing C_f, 25% aircraft drag reduction	• Explore active & passive LFC concepts; resolve system R&M questions & exploit "active" skin
Supersonic	• Active control work done in 1960's	• Can have significant effect on C_f & reduce equilibrium surface temperatures	• 80% wing and body C_f, 30% aircraft drag reduction • Skin temperature reduction of 160° at M = 3.5	• Continue to develop systems & data base
Turbulent drag	• Recent work with nonplanar wall & turbulence modification devices shows promise • Data base for low speed only	• Potential for significant drag reduction on fuselages, nacelles, pods, etc.	• 30% fuselage C_f reduction at subsonic M, 15% at M ≥ 1	• Expand studies of wall geometry, turbulence modifiers, & pressure gradient modification • Extend to higher Mach flows
Wave drag	• Slender bodies & thin wing data base is extensive • Variable sweep has been exploited	• Significant reduction can result from blending & flow control	• 40% wave drag reduction at cruise	• Revisit wave cancellations schemes, flow field blending designs, variable geometry, and BLC to reduce shock strength
Drag due to lift	• Aspect ratio effects well known • Winglets used effectively	• Improvements possible in many applications	• Tailored concepts to specific applications to reduce C_{D_i} up to 40%	• Revisit strut-braced wing, ring wing concepts, joined wings • Optimize tip devices, tip blowing, tip nacelle, etc. • Tailor camber & twist
Interference drag	• Tailored for specific designs • External store/ nacelle/pylon effects being studied	• Improvement can be expected as tools evolve to better define the flow fields	• Reduce external weapons carriage drag by 60-70% • Significantly reduce body surface juncture drag	• Exploit favorable interference for stores carriage • Blend intersections, use eddy break-up devices to improve boundary layer
Rotorcraft fuselage drag	• Inviscid theory combined with boundary layer calculation, prespecified fuselage and rotor wake	• Optimized fuselage and hub design will result in increased speed and/or range	• Rotorcraft fuselages with (1) no adverse effects of rotor flow, (2) negligible flow separation (60% fuselage drag reduction)	• Apply unsteady Navier-Stokes codes which include rotor wakes, fuselage separation, and empennage flow fields in conjunction with parametric optimization

Note: Targets are relative to current operational systems.

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Table 1-4 Aero/Propulsion Integration

	Status	Projection	Target	Possible Approach
Inlets & airframe/ inlet integration	• Satisfactory design for performance but often heavy with long diffusers • New and unique inlet shapes being studied	• Efficient, lightweight short diffuser, variable capture inlets feasible • Top mounted, flush and exotic aperture designs to increase survivability	• Compact, variable capture area ratio inlets with subsonic diffuser l/d ≤ 2 • Inlet/engine less sensitive to α and Mach to Mach = 6 • Unconventional inlet aperture with recovery and distortion comparable to conventional inlets	• Exploit tailored bleed systems, blowing and flow control concepts to insure flow quality • Apply evolving CFD tools to refine design of inlet and installation details, utilize viscous flow control
Nozzles & airframe/ nozzle integration	• Large data base for axisymmetric nozzles and evolving base for nonaxisymmetric	• Highly efficient integrated nozzles with reduced observables possible	• Installed nozzle drag reduction of 50% • Significant reduction in plume observables	• Apply evolving CFD methods to integrate non-axisymmetric nozzles • Evolve nozzle/plume shaping & mixing techniques to reduce observables
Thrust reversing/ vectoring (TR/TV) nozzles	• Practical TR/TV nozzles demonstrated for STOL applications	• Lightweight TR/TV nozzles to make new uses for STOL and maneuvering possible • Blending of aero & reaction controls to impact missile capability	• TR/TV nozzles for STOL takeoff length reductions of 80% and augmentation and/or replacements of control surfaces	• Exploit evolving CFD and experimental techniques to optimize the intersecting flow fields and assure optimal flight control • Optimally blend reaction and aero controls
Propulsive lift	• Many propulsive lift methods (jet flap, blowing, blown flaps, etc.) investigated to date • Limited usefulness because of device weight and thrust loss due to high engine bleed	• Techniques for effective generation of lift with low engine bleed possible	• Double usable maximum lift at low engine bleed rates • Increase L/D by 25%	• Develop circulation control concepts which are feasible with minimal blowing
Rotor design	• Simple blade element theory with prescribed wakes/empirical data base	• Rotor designs with improved performance, low noise and low vibration loads	• 50% vibrating load reduction • Sideline noise levels below FAA standards • 20% increase in L/D or less required hub torque	• Apply CFD, detailed experiments to optimize rotor dynamics • Utilize viscous flow control to optimize rotor performance

Note: Targets are relative to current operational systems.

Table 1-4 Aero/Propulsion Integration (cont'd.)

	Status	Projection	Target	Possible Approach
Circulation control rotor	• Circulation control airfoil largely empirical • 3-D and unsteady effects unknown essentially	• Rotorcraft capable of maneuvering transonic flight	• Efficient cruise at C_L of 0.4 at M = 0.8	• Develop CFD and conduct detailed experiments (including flight) to optimize circulation control
Aero and propulsive force blending and control	• Available force management trades for aero and performance insufficient to date	• Emphasis to place most offense and defense functions on the missile instead of aircraft • Immediate control of weapon after launch	• Optimization to permit missile slew of 180°	• Study sensitivity of controls to dynamic pressure to allow optimization of maneuver and control
Hypersonic aero-dynamics/heating	• Analytic methods are largely empirical but advancing rapidly • Limited data base for shock interactions, vortex interactions, flow separation and attachment, surface/shock interactions	• Accurate flow field and heating prediction method will allow multi-parameter design of configurations, precise controls, and propulsion system integration • Active cooling techniques for heat transfer reduction and reduced observables	• Accurate predictions of force and moment characteristics across the complete flight range including propulsion integration • Efficient advanced propulsion concepts • Reduced cost of experiment to give a comprehensive data base	• Develop computational and experimental capability to provide design and analysis tools • Exploit advanced propulsion and active cooling concepts
Ejector thrust augmentation	• Installed augmentation ratios of 1.2 demonstrated. Uninstalled ratios of 1.6 achieved at small scale.	• "Cool" footprint VTOL possible for high performance aircraft	• Installed ejector augmentation ratio of 2.0	• Blend configuration and ejector geometries with flow control devices to prevent diffuser stall
Turboprops	• Propeller research dormant from 1955 to 1975 • NASA active in M = .7-.8 turboprop research since 1975	• Significant improvement in prop efficiency and reduction of installation losses	• Turboprop design for 40% savings in block fuel for M = .8 cruise	• Improve aero modeling for propellers • Minimize swirl losses (e.g., counter-rotating propellers, stators) • Explore installation alternatives to reduce drag
Turbofans	• Successful fan and nacelle designs evolved over past 25 years for M < 1 • Supersonic through-flow fan studied for high speed aircraft	• Attractive improvements in fan and nacelle aero possible • Supersonic flow fan with near zero length fan inlet and nozzle	• Advanced turbofans (HBPR 9-13) to give 7% block fuel savings • 15% reduction in block fuel for M = 2.5 cruise	• Swept fan blades • Slim short low-drag nacelles • Shockless M > 1 fan

Note: Targets are relative to current operational systems.

Table 1-5 Vortex Management

	Status	Projection	Target	Possible Approach
Delay and control of separation	• Current fighters employ strakes to improve L/D and handling qualities • Vortex augmentation studied, e.g. spanwise blowing • Analytical design capability insufficient • Exploratory work has been done on several concepts including locked vortex in cavities	• Controlled vortex flow will enhance maneuverability and give departure-free flight capability and improved high-angle-of-attack L/D • Fixed geometries will provide viable separation control techniques for diffusers, afterbodies, and controls	• Departure free flight capability • Optimized maneuver capability (roll rate, pitch rate, buffet free) with active vortex control/flight control coupling • Non-movable fluidic control surfaces • Afterbody drag reduction • Very short diffusers	• Exploit active (blowing, variable geometry) & passive (chine, strakes) vortex control methods • Develop understanding of vortex phenomena and CFD models to aid design • Develop geometry and suction stabilization techniques to lock vortices at critical locations, especially at high Reynolds numbers • Continue optimization of longitudinal grooves and vortex generators
Wake vortex minimization	• Vortex attenuation/ redistribution methods exist, but physics not well understood	• Control vortices can be generated to alter the tip vortex and thus increase airport productivity	• Improve airport takeoff and landing separation time by 50%	• Explore vortex attenuation techniques using geometrically generated control vortices • Understand physics of interacting free vortices in free atmospheric turbulence.

Note: Targets are relative to current operational systems

Table 1-6 Configuration Synthesis

	Status	Projection	Target	Possible Approach
Emerging vehicle concepts	• Wind tunnel testing plus extensive existing data base for conventional shapes • Several requirements and disciplines entered off-line into design synthesis programs	• New requirements (such as low observables) to drive configuration to unconventional shapes • New and innovative design tools and data base to be developed	• Cost effective integrated designs employing new technologies to meet future requirements • Aerodynamics totally integrated with advances in other related disciplines	• Take full advantage of CFD and conduct configuration research to establish methods and data base on new and innovative vehicle shapes • Integrate all requirements and disciplines into a design synthesis program that accommodates future vehicle shapes (multi-parameter design)
Hypersonic vehicle concepts	• Emphasis on importance of hypersonic flight re-emerging	• Vehicles with advanced heat shielding concepts employing active cooling	• Methodology to accurately predict forces and heating across flight regime from free molecule to continuous flow • Active cooling application	• Use of favorable interference for high L/D • Research aerodynamics of low density flight • Exploit CFD
All weather operation - icing	• Research in U.S. dormant from mid 1950's to 1978 • Current ice protection system design based on limited analysis	• Refinement of existing and new unique ice protection concepts • Streamlined low-cost certification procedure that emphasizes analysis and ground facility tests	• Adv. prediction methodology for designing light, reliable, low power ice protection systems • Accurate analysis method for predicting ice buildup and minimizing impact on aircraft aero for unprotected components	• New test techniques and experimental modeling • Advanced de-icer concepts: Electro-impulse, Fluid systems, Electrothermal, Piezo electric, Microwave, Boots • Exploit CFD to predict droplet trajectories, ice build-ups and separated flow

Note: Targets are relative to current operational systems.

Report of the Panel on

Propulsion

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PROPULSION

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PROPULSION

Introduction

Propulsion, while conventionally included on the list of important aeronautical disciplines along with aerodynamics, structures, etc., is in itself a systems endeavor, analogous to the engineering of the entire vehicle; indeed propulsion encompasses important aspects of all the other disciplines. In recognition of this fact, the panel focused its discussion on those aspects of the key disciplines that are especially or uniquely important to propulsion.

From the initial development of the airplane, the propulsion system has been recognized as one of the pacing technologies. It is perhaps because of the technological disparity between the reciprocating engine and the primitive airframe that the two remained relatively and separately developed somewhat independently, usually by different organizations.

In recent years, the maturing of the gas turbine power plant and the advance in high-speed airframes have rendered this separation somewhat artificial. The power plant and the airframe now share common structural and aerodynamic elements; as the flight Mach number rises, the degree of interaction increases. By the year 2000, this interdependence will have increased in many respects to a point where independent design may not be practical or possible.

During the period since the initiation of the aircraft gas turbine, the solid propellant rocket and the liquid propellant rocket, a vast array of other novel engines have been studied, covering the full spectrum of flight conditions from low subsonic to hypersonic and transatmospheric flight. In each instance, performance limits have been investigated under the assumption that current technology or reasonably foreseeable technology would be available for their development. Among the extensive list of advanced, high-performance concepts and cycles examined are the hypersonic ramjet, the variable cycle, runway-to-orbit airbreathing engine, the ram rocket (air-breathing and rich solid propellant rocket), and the air turborocket.

At various times, these systems have come relatively close to meriting development and application. In many instances, limitations of materials and technologies curtailed development. As important and with almost equal frequency, the lack of commercial or military utility of the concept precluded the necessary funding.

It is instructive to note that two former items on this list--the turbofan (bypass engine) and the high-speed turboprop--are respectively a mainstay engine and a promising development. In the case of the turbofan, its full potential could not be realized until turbine cooling technology had been developed and new materials developed to

permit the construction of transonic fans. In the case of the high-speed turbopropeller engine, not only were the material and turbine technologies needed, but, in addition, the rise in fuel costs provided the impetus to take advantage of its favorable fuel consumption characteristic.

As the basic technologies progress and as new missions become attractive, the engines in the foregoing list become candidates for new feasibility studies and further technology development. At the present time, the ram rocket is the prime contender to augment the range of small missiles. Of interest also is the hypersonic ramjet and its logical extension, the runway-to-orbit airbreathing engine.

Much of this report deals with the development of current or near-future power plant concepts. First, the motivating factors for aeronautical propulsion research are reviewed as a reminder of the importance of continued effort in a field that has often been characterized as mature. Next, technical areas are discussed in which the panel feels additional research effort is warranted and would lead to the realization of the technological potentials between now and the year 2000. Under these guidelines, new cycles (e.g., isothermal energy exchange) were not considered by the panel.

Finally, although facility requirements were not a prime consideration in the current projections, the panel believes that the increasing complexity of propulsion systems; the need for more refined interaction between propulsion system, airframe, and controls; and increasing operation in adverse weather will require test capabilities beyond those now available (see appendix). Enhanced test capability is needed in the areas of propulsion airframe integration and in large-scale icing research with proper concurrent treatment of altitude, temperature, and speed.

Further information on materials, structures, and controls related to propulsion systems is given in the reports of the Panel on Materials (pp. 109-120 and 126-128), the Panel on Structures (pp. 77-78 and 81-84), and the Panel on Guidance, Navigation and Control (pp. 155-156).

The Importance of Propulsion R&T

While the importance of propulsion to aeronautics generally is accepted, four points need emphasis: (1) propulsion is a limiting factor in aircraft performance; (2) the aircraft engine market is very large; (3) the trend of the industry is toward cooperative international programs; and (4) new propulsion system concepts need the support of a strong research program. Advanced propulsion systems derived from an enhanced research and technology (R&T) development program hold the key to successful development of future air vehicles

such as high-speed turboprops, short takeoff and/or vertical landing (STOVL) aircraft, convertible rotorcraft, low radar signature aircraft, and hypersonic and transatmospheric vehicles.

Propulsion is a limiting technology for both commercial and military aircraft. Increased propulsion capability is almost a requirement for initiating development of a new aircraft. This can take the form, in the case of commercial aircraft, of a requirement for lower fuel consumption or lower noise. For military aircraft, it could take the form of reduced fuel consumption, a higher thrust to weight ratio, and/or longer engine life. Supersonic cruise transports await a fully satisfactory propulsion system, as do vertical takeoff and landing aircraft. Thus, there is a strong incentive both to improve the performance of conventional aircraft engines, and to conceive and develop new, more efficient, and powerful propulsion systems.

In terms of cost, maintenance, and replacement, the propulsion system accounts for two-thirds of the life cycle cost of a commercial transport. In addition, the engine has a major effect on fuel cost. Improvements in propulsion system technology can offer a large economic return for the investment in research and technology development.

The market for new aircraft engines is estimated to be $150 billion over the next decade--split equally between commercial and military. The market is a highly competitive one in which the best technology is usually the key to success, especially in the commercial sector. It is critically important to ensure that U.S. engine manufacturers continue to compete successfully in this market, and it is essential, therefore, that necessary support be provided to pursue all promising technology advances.

While the U.S. engine manufacturers have succeeded very well in the past, there are signs of a fundamental change in the aircraft engine business. In the past, each major engine manufacturer has been able to marshal the resources needed to design and develop engines, from research through development; but as the sophistication of the technology has grown and the cost of new engine development has risen, there has been a trend toward more joint international developments, many of which involve U.S. companies. One consequence of this trend is likely to be a reduction in the commitment of each individual company to in-house research, since its ability to capture its benefits will be reduced by the collaboration. To maintain the desired pace of the overall U.S. research program, it will be necessary for the U.S. industry and government to join together in a cooperative program of basic research on which all of the U.S. industry can draw and, thus, to ensure that the United States continues to be seen as a desirable partner in international combines.

The enhancement of propulsion R&T described here can be fully justified by the improvement in performance of existing propulsion

systems. An additional powerful motivation is several emerging propulsion concepts that will benefit in major ways from the technology advances. Some of these are the high speed turboprop, STOVL aircraft, and convertible rotorcraft. For the full development of low signature aircraft and for hypersonic and transatmospheric vehicles, enhanced R&T is deemed critical.

High Payoff Technology Projections

Ten technological areas have been identified in which projected technology advances would have major impacts on propulsion systems of the future. The present status and the potential improvements will be outlined for each of these areas. Within this group of 10, 5 "critical" areas have been identified which, in the opinion of the panel, hold exceptional promise for improving propulsion system performance, weight, or cost. In the following list they are identified by asterisks, and they are discussed first and given special attention in the following discussion.

*Internal computational fluid mechanics (ICFM)
*High-temperature materials
*Heat transfer
*Propulsion system instrumentation
*Advanced controls--"smart" components
Centrifugal compressors
Mechanical components
High-temperature composites
Engine structural dynamics and aeroelasticity
High-speed propulsion.

Internal Computational Fluid Mechanics

Computational fluid mechanics, as it applies to propulsion, involves understanding and predicting the flow fields of engine components (e.g., inlets, compressors, combustors, turbines, and exhaust nozzles). The research involves numerics, mesh construction, code efficiency, algorithms, and physical modeling. An effective program requires a balanced approach between numerical modeling and experimental research.

Status Internal computational fluid mechanics (ICFM) represents a major opportunity in propulsion to improve productivity in the design/development process and to overcome technical barriers that limit engine performance. The generation of efficient ICFM design tools and methodologies would have a major impact on cost and development time of future propulsion systems. In addition, advances in ICFM would allow for quantitative evaluation of advanced and revolutionary propulsion system concepts.

Key research activities in the area of internal computational fluid mechanics include physical modeling, algorithms, numerics, mesh construction, code efficiency, and graphics. Physical modeling involves improved mathematical representation of physical processes.

ICFM is now approaching a level of maturity in which the limit to applicability is not so much inadequate technique or even computer power, but rather a lack of full understanding of flow turbulence. This is not to say that improved techniques and algorithms would not be useful or that computer power is not a limiting factor, but that all high Reynolds number flows are fundamentally unsteady and that one will continue to have limited accuracy if only steady-state models are applied.

One aim of ICFM is to achieve satisfactory technological solutions, but possibly as important is the effort to advance physical understanding of the situation, a result requiring more than empirical research.

Projections At the present pace of evolution of computational algorithms and development of computational power, there almost surely will be a capability, by the year 2000, to compute the 3-D viscous flow in fans, compressors, and turbines, with sufficient dispatch to make the process useful in design.

This will permit quantitative design trade-offs in which the aerodynamic performance is balanced against weight, structural characteristics, and perhaps even cost. Quantitative predictions of hot section heat transfer will be possible, enabling more uniform metal temperatures, lower cooling flow rates, and providing longer hot section life.

Computational fluid mechanics also will benefit the area of flows with chemical reactions. Combustion in a turbulent fuel-air stream has additional complexity and, therefore, additional equations to solve. However, where the combustion process is flow dominated, as is the case with the gas turbine combustor, progress is being made in the ability to calculate these flows. By the year 2000, a steady-state calculation with chemical reaction, represented by 2-step or possible 4-step processes, and with a turbulence model that can predict reasonably the mixing in 3-D swirling flow fields, is achievable. Efforts in time-dependent numerical techniques also are promising, but are not expected to be as advanced as steady-state codes. The numerical models will present the combustor designer with much more powerful tools, which should lead to combustors with high-performance (even at off-design conditions), improved durability, and a shorter, lower cost design and development cycle.

High-Temperature Materials

Engine materials have paced the progress of propulsion from the inception of the turbine engine and will continue to do so for the foreseeable future. Two major thrusts in engine materials are foreseen in the next few decades: the introduction of lightweight nonmetallic structures and the progressive substitution of ceramics for metals in the hot section of aircraft engines.

Status The evolution of hot section materials will proceed in three areas: the continued development of metallics, especially anisotropic superalloys; thin layers of ceramics as a thermal barrier; and solid ceramics. Continued progress in superalloys is likely to yield an improvement of 200°F in allowable metal temperature before fundamental melting point limitations are reached. Ceramics presently are being used in burner liners and vane platforms as a thermal barrier. The thermal barriers are being used to gain extra durability; but they also have a tendency to spall, and this has prevented more widespread use. The next decade will see the further use of thermal barrier coatings as a "prime, reliable" part of the airfoil.

The most important activities for the continued use of metallic airfoils are to develop the composition, materials control, processing technology, and the design system necessary to achieve the full 300°F benefit associated with prime reliant thermal barrier coatings. In addition, systems that leapfrog current melting point limitations will be of continued interest.

The three main technical thrusts needed to create the technology base to improve ceramic material reliability/reproducibility are materials and processing, design methodology, and life prediction. The overall objectives of these major thrusts are to understand the relationships between materials, processing, microstructure, and properties, and to apply this understanding to improve design tools for brittle materials and to improve the capability for accurately predicting the lives of ceramic components. An integrated interdisciplinary approach is required for ceramic materials technology.

The application of ceramics to engines will proceed in several stages. Presently, a thin layer of ceramics is used as a thermal barrier coating in combustors and vane platforms. The ceramics are used as a life extender rather than as a prime, reliable part of the design that takes full advantage of the ceramic material. Further use of ceramics as a structural material will proceed in vanes and combustors, although it is highly likely that significant design changes will have to occur in order to utilize fully these brittle materials.

Projections Advances in high-temperature materials by the year 2000 offer the possibility of materials able to withstand temperatures

400°F to 600°F higher than today's materials can, assuming sufficient basic work is accomplished. The turbine blade materials in this time period most likely will be advanced versions of the present single crystal-type systems with increased dependence on thermal barrier coatings to reduce cooling requirements. However, it is highly likely that combustor and turbine vanes will be made of ceramic or ceramic/composite structures. This application will be the first to take advantage of the brittle, high-temperature materials. The mechanisms of thermal barrier coating degradation and failure will be understood so that coating systems can be exploited fully. The advanced alloy systems must not be significantly more expensive than the present compositions.

Advanced propulsion systems will utilize high-speed rotors requiring high-strength disk materials. Hybrid materials will be developed with local composite reinforcement.

The future development of present superalloy systems would allow 100°F to 200°F improvement in metal temperature capability, while systems with fiber reinforcement can yield an additional 100°F to 200°F. Ceramic materials offer 400°F to 600°F temperature capability increase and have a significant market potential. To date, ceramic materials have demonstrated good high-temperature strength and oxidation resistance but have shown poor reliability and reproducibility.

Eventually, solid ceramics will be used in engines. The first use of solid ceramics will be in the stationary portions of the hot section, e.g., vanes or vane platforms of fabricated airfoils. Further in the future, blades and disks will use nonmetallics. In addition, fiber reinforced materials eventually may be introduced into hot sections and alternate technologies should be investigated because of the enormous payoff of advances in material capability.

Heat Transfer

Heat transfer is that part of fluid dynamics which forms the basis for defining the thermal environment that the propulsion system is exposed to throughout the operating cycle. It includes understanding complex flow phenomena in and around rotating and static components for both steady-state and transient operation as well as in inlets and nozzles for high-speed flight. Heat transfer encompasses the development of analytical models capable of accurately predicting the time-dependent temperature distribution within parts, thus enabling structural design optimization and accurate prediction of stress, strain and life.

Status In the hot gas flow path portion of the propulsion system, temperatures are much higher than the component materials can withstand, and sophisticated cooling schemes are required to protect the components. A different type of heat transfer problem occurs outside of the hot gas flow path. Here, the components are surrounded by gases that are at temperatures well within the general capabilities of the component materials. However, the temperature distributions in the components must be known so that dimensions, clearances, and thermal stresses can be calculated. These heat transfer problems outside the hot gas flowpath require detailed attention.

A major problem in the hot gas flow path is the quantification of the environment in terms of the factors influencing the heat fluxes to the component surfaces. This is extremely difficult because of the complex flow phenomena involved. In the turbine, for example, the heat fluxes are influenced by strong acceleration fields, laminar to turbulent boundary layer transitions, concave and convex curvatures, free stream turbulence, time-dependent wake effects, and film cooling. In the combustor, the phenomena are somewhat different but no less complex. The high levels of turbulence and the radiative heat transfer caused by the combustion process make calculations of the heat fluxes in the combustor very difficult. The heat fluxes to other components such as augmentors and exhaust systems are governed by similarly complex flow phenomena. Evolution of methods for quantifying the hot gas flow-path environment is proceeding slowly and requires extensive effort.

Away from the hot gas flow-path, the most critical problems appear to be involved with the flows and heat transfer around rotating disks. The rotating disks cause viscous pumping which, in turn, causes a requirement for coolant purge flows. In addition, airflow transients can cause heat transfer to the disks with significant thermal stresses. The flow and heat transfer characteristics around rotating disks require much further investigation.

Concentrated research in propulsion system heat transfer is needed to predict and control transient and steady-state metal temperatures of critical gas turbine engine components. If prediction and control of metal temperatures can be achieved with a high degree of accuracy, then engine durability and performance can be improved significantly. For example, the creep life of a turbine blade can be changed by a factor of 2 by a 25°F change in average metal temperatures. Metal temperature cannot be predicted to that degree of accuracy today, and therefore, an overly large design margin must be utilized or extensive engine testing must be performed to produce durable engine designs. Neither alternative is acceptable, because a large design margin means using excessive quantities of cooling air, which degrades the thermodynamic cycle, and extensive engine testing is very costly.

In order to improve performance there is a continuing need to increase turbine inlet temperature. In military aircraft, this need arises from the desire for more thrust per pound of engine weight. In commercial aircraft, this need stems from the desire for higher thermodynamic efficiencies. With current technologies, higher turbine inlet temperatures can be achieved only by increasing cooling flows, and the level of cooling flows is becoming unacceptably high. Advances in turbine cooling technology are, therefore, required in order to permit these higher turbine inlet temperatures without requiring excessive cooling air.

The present state of propulsion system heat transfer is dominated by large uncertainties in the knowledge of actual operating temperatures and heat loads imposed on parts. Average metal temperatures can be predicted fairly well, but local conditions can be in error by 100°F to 200°F. Unfortunately, problems like cracking and burning are caused by local hot spots, so it is the local detail of temperature that must be known in order to predict life. This is particularly true when a propulsion system represents a large departure from the existing configurations of a manufacturer, such as the main engine of the space shuttle or hypersonic vehicle propulsion system.

The problem of propulsion system heat transfer is compounded by the difficulty of obtaining measurements in the actual operating environment. The harsh operating temperatures require new techniques in instrumentation and data handling. Also, the local nature of hot spots caused by end wall flows and separations requires that information be obtained all over the hot section in great detail and very close to the walls.

Projections By the year 2000, heat transfer technology is projected to be developed to provide propulsion systems designers with information to allow substantial improvements in gas turbine engines. It will allow design optimization of coolant and secondary flow systems, such as seal leakages and thermal control circuits, and yield small but highly valuable performance increments on the order of 3 to 4 percent in thrust or power and around 2 percent in fuel consumption without resorting to additional complexity or cost.

The area of greatest performance payoff is in the enhancement of hot parts; e.g., turbine blades and vanes, temperature capability by improved circuit design and higher cooling effectiveness, and optimization of coolant distribution. This can yield an increase of about 50°F in engine firing temperature, which normally yields 6 to 8 percent increase in thrust performance. But the greatest benefit of heat transfer as a design discipline is the ability to predict temperature distributions within parts to an accuracy wherein the calculated stress and strain behavior of the part truly predicts part life during the design process. The current methodologies require temperature measurement of flow and metal surfaces during the development process

well after initial test of the product. Design iteration is a long and extremely costly approach to problem solving and, thus, becomes a major detriment to engine development initiatives. Good heat transfer methodology is critical to reducing development time and cost and to maintaining U.S. preeminence in propulsion products.

Projected advances in heat transfer capability will allow the average temperatures of a 3000°F component to be predicted within 10°F. This increase in capability will lead to enormous reductions in development time and cost. For instance, a large gas turbine development program could involve 10 to 15 experimental engines with 3 to 5 of the engines devoted solely to durability work. The program could cost $500 million, and it is not difficult to foresee that 25 percent of the cost could be saved if hot section uncertainties were eliminated. Also, the reductions in temperature uncertainty will allow more refined cooling air estimations, thereby allowing higher thrust-to-weight configurations.

Propulsion System Instrumentation

There are tremendous weaknesses in existing sensor and instrumentation technology for airbreathing propulsion. Advanced sensor and information transmission and processing capability are required to meet research and production application requirements. Nonintrusive techniques, enlivened by the explosive growth in electro-optic technology, offer possible quantum step advances in gas turbine instrumentation. Since the gas turbine environment is often the absolute constraint on instrumentation applicability and performance, care must be taken that this development is carried out under realistic conditions.

Status The capability to analyze and calculate information has far outstripped current ability to acquire information in realistic engine environments. Thus, the understanding of the physical processes in aircraft gas turbines has been greatly constrained by the limited ability to make direct measurements in the real environment, in both laboratory as well as in operational engines. This is due primarily to the very harsh nature of the gas turbine environment, the individual components of which (very high temperature, high pressure, adverse oxidation environments, a high degree of unsteadiness, and 3-D phenomena) may be present in other man-made devices, but not simultaneously as in the gas turbine. The result is that instrumentation developed for other than gas turbine applications cannot be adapted readily. In an operational engine, this means that one must often measure not the physical quantity of interest, but one within the capability of the sensor technology followed by quasi-empirical modeling to infer the desired variables.

Instrumentation technology requirements are driven by both research and operational needs. In research, the need is to explore in detail the physical processes inside an engine environment in order to understand the fundamental phenomena. Verification of newly developed analytic tools is also a driver. For production engines, very high sensor reliability is of paramount concern and is an important constraint on the development of improved sensor capability for engine control, diagnostics, and performance retention.

Technological advancements for propulsion system instrumentation can be grouped into four general categories: (1) increased spatial resolution (now often less than the physical quantities of interest, e.g., boundary layers); (2) increased spatial coverage (now only a few points throughout an active volume); (3) increased frequency response (now DC in fields fluctuating to first order in the kilohertz range); and (4) in particular, durability and reliability. It should be noted that the technology required is not just that of sensors, but also sensor information transmission and processing.

Specific target areas for new instrumentation techniques include: flows near surfaces (airfoils and end walls); rotating frame measurements of flow and stress; hot section measurements (metal and flow temperature, stress, heat flux, etc.); in situ structural assessment (flaw detection, creep, etc.); and improvement in sensor life and reliability.

Projections By the year 2000, sensor technology is expected to have advanced to the point where comprehensive hot section measurements can be done routinely during development, operational engines will contain large numbers of high-reliability sensors, and in situ structural assessment will have become widely used.

Advanced Controls--"Smart" Components

The use of real-time intelligence in closed-loop control can be used to improve performance and operability of propulsion system components and subsystems (inlets, fans, compressors, turbines, nozzles, etc.). The basic premise is that advances in onboard processing capability and sensor technology will make it feasible to incorporate feedback control within engine components in order to optimize engine performance and life.

Status Key activities in this area involve the identification of ways to use real-time intelligence to improve propulsion system controls. Some areas where this technology can have a significant impact include compressor stall alleviation, active clearance control, secondary airflow modulation, and active pattern factor control based on blade stresses or temperatures. In order to achieve the potential benefits,

improved sensor/computer/effectuator systems and improved component models must be developed.

Aircraft gas turbine engines traditionally have consisted of an integrated set of highly engineered open-loop subsystems with a feedback fuel control. Only a few sensors are used as input to a simplified, semiempirical engine model upon which the controller is based. This control scheme has been dictated by limited onboard computational capacity and inadequate sensor reliability and environmental capability.

Projections All near term applications of advanced control technology will be in use by the year 2000 and, possibly, active stall alleviation and pattern factor control will have been demonstrated on the test stand. The continuing microelectronic revolution implies that the onboard computational capacity (both processing and storage) will increase by orders of magnitude over current systems. This increase in capability can and will be employed to improve greatly the traditional engine fuel control (increased model fidelity, adaptive control, nonlinear models, fault tolerance, etc.). It also could be used to alter fundamentally the nature of gas turbine components and subsystems from open to closed-loop operation resulting in more optimal performance through design conditions.

Centrifugal Compressors

Improved centrifugal compressor technology requires the development of the design capability to achieve high pressure ratio at efficiency equivalent to axial compressor technology. The internal flow of the centrifugal compressor is not well understood. In general, the flow in the impeller separates at or near the leading edge of the inducer. This separation results in a relatively small high-pressure jet and a large separated wake at the impeller exit, which mix violently causing large pressure losses. High wheel-tip-speeds result in transonic relative Mach number at the diffuser entrance. The resulting diffuser shock system thickens the boundary layer at the diffuser throat and results in low diffuser recovery. If these technical issues could be resolved, moderate-size compressors could produce relatively high efficiencies.

Centrifugal compressors have the potential of high compression ratio at low corrected air flow (pressure ratio of about 10 to 15, weight flow rate of approximately 2 to 3 pounds per second), however, the present state of the art is such that efficiency is much lower than for equivalent axial compressors. Efficiency goals up to 90 percent should be expected for moderate size compressors and could be realized if research were expanded to develop a basic understanding of the fluid flow in impellers and diffusers through

o development of analysis methods that accurately describe the flow;

- development of modern design methods;
- investigation of methods of passive and/or active boundary layer control; and
- conduction of experimental efforts that support the analysis methods and help unravel the complex flows.

With the successful completion of such work there is a growing potential for the use of high-performance centrifugal compressors in intermediate-size turbofan/prop fan engines where axial compressor blade height becomes unrealistic for acceptable efficiency and in advanced helicopters for civilian and military use.

Mechanical Components

Improvements in key mechanical components of turbomachinery and power transfer systems are required to prevent these elements from limiting the improvement of performance and reliability of advanced propulsion systems. Among components that are nearing limits are mainshaft bearings and seals; turboprop gearing, bearings, shafting and structures; rotorcraft transmissions; and higher-temperature lubrication system components. In addition, improvements in accessories and associated drive systems can have significant payoffs in weight, size, and efficiency, and, therefore, in improved overall performance and reliability.

Status As emphasis on improving propulsion efficiency builds, by investigations into advanced propeller concepts and higher fan bypass ratios for subsonic transport applications, the need for related improvements in mechanical components increases.

Further, increased thrust to weight for high-performance military aircraft drives the requirement for lighter aircraft engines. At the same time, however, such engines must have low life cycle cost. This can be attained only by integrating key engine structures and becomes very dependent on the ability of the engine designer to find advantageous configurations. Mechanical components can constrain structural configurations such that their influence on engine weight and cost far exceeds the actual weight and cost of the summed components.

Improved fundamental understanding of stress, strains, defects, fretting, wear characteristics, heat generation, traction, asperity interaction, and material/lubricant interaction is required to advance this area of technology. Improved life and reliability and the capability to predict the life and reliability are required.

Higher-speed mainshaft bearings and seals would be addressed as part of the effort on mechanical components. This would include the fracture toughness characteristics of the materials, the slip/clearance criteria for cylindrical roller bearings, as well as the life capability at these extreme conditions. Rotor dynamic effects must be considered.

To increase the power density of gearboxes and transmissions, increased capacity bearings are required. Materials, geometry, lubricant, and design method improvements offer the greatest payoff. Improved lubricants also would have payoff in the load carrying capacity of the gearing. Areas of lubricant improvement include increased load-carrying capacity and increased temperature capability. The degree of accuracy in determining deflections must be improved significantly. Conformal gear theory, modeling, and analysis would be accomplished with the aim of increased load-carrying capacity or a reduced number of stages.

Traction drive research would be concentrated on their use in the development of servo mechanisms with high torsional stiffness. A second use for traction drives may be in the accessory arena. Also, in the accessory area, research into increasing the speed of these components offers significant payoff in size and weight which then provides performance gain.

In the area of power transfer, new shafting/coupling technology has significant payoff potential. Lightweight metallic and nonmagnetic shaft technology as well as new manufacturing techniques would be investigated.

Mounting dynamics for turboprop and rotorcraft transmissions may be improved by some new concepts for varying restraint and damping for torque isolation and antivibration mounting of high torque transmissions. Tuning of these systems by the use of microprocessors may offer significant reductions in weight and noise and transmissibility of vibration loading.

Projections A continuing effort in mechanical components technology can yield main shaft bearings and seals capable of meeting reliability requirements at speeds of 3.5 million DN. This implies that failure initiation mechanisms can be understood and that designs do not have "immediate" total failure at the time of initiation, but have a time period of degraded performance. Such bearings and seals will simplify engine configurations yielding weight and cost reductions. This is important today, but it will be far more important in the future as propulsion efficiencies increase through high bypass ratio for turbofans or even higher mass flow propfan systems, and as core engines operate at higher temperatures for thermal efficiency and decrease in size.

By the year 2000, mechanical component technology can provide reduction-gear systems far superior to those that can be developed for the high-power (20,000 to 30,000 pound thrust) prop fans needed for future subsonic transports. Improvements in power/weight and power/volume of about 2 can be projected. It must be done with greater life and reliability than can be obtained with today's technology, which requires that a far better understanding of failure mechanisms and parts life of high-capacity bearings and gears be developed.

It is possible that controlled response between engine rotating components and static structure and/or between engine structure and airframe structure would be available by the year 2000. Thus, failures that ordinarily would produce high loads and possible severe damage and structural failure can be accommodated to allow continued operation at reduced power and mission completion, or, at least safe operation.

High-Temperature Composites

Advanced aircraft systems will continue to follow the trend of improved efficiency, reduced operational cost, and higher payload capability largely due to improvements in propulsion systems. Composite structures are an integral part of engine and propulsion system improvement as they are lighter in weight and more cost-effective than corresponding metal components. In order to maintain this propulsion system trend, increased composites usage in the engine will be required. The extended use of composites in today's engines is limited by the operating temperature limits of the available composite system. Development of current composite systems has allowed the fabrication of engine parts for operation up to 550°F at reduced weight and cost. Usage of composites in major engine structures can be expanded vastly if higher temperature capability can be achieved. The goal is development of a processible polymeric composite material system capable of operating at temperatures approaching 1000°F for application to complex engine structures such as frames, casings, stators, and ducting.

Status The key issues to be addressed for an advanced, higher-temperature composite include the identification of a polymer and fiber system with adequate oxidation stability, material properties, and polymer processing capability. The major obstacle in higher-temperature composites development is thermal oxidation for both the matrix and the fiber. Oxidation causes material change resulting in weight loss and reduction in strength, the degree of which depends on time at temperature. For T300/PMR15, strength reductions of 10 to 35 percent have been observed for exposure times of 100 hours at 500°F with weight loss in the range of 2 to 3 percent. For longer times approaching 1,000 hours' exposure, weight loss is considerably higher with corresponding strength reductions.

Once an acceptable candidate high-temperature composite system is identified, material property and failure mode characterization must be accomplished. Properties at temperatures approaching 1000°F equal to the current PMR15 system at 500°F should be the goal.

Projections Current effort in polymer technology is aimed at the development of a 700°F polyimide composite system for the 1990 time period. The effort to develop the required technology includes teaming government agencies, suppliers, and universities to address the key issues.

The probability of developing and implementing a suitable composite system for temperatures approaching 1000°F by the year 2000 appears possible, assuming a comprehensive effort including multiple independent approaches of the major issues is undertaken. If this polymer program developed an 800°F to 900°F capability only, it would still go a long way toward providing composites for future engine systems. Advanced composites are mandatory to maintain the trend of reduced weight and cost in spite of increased operational capability and will enhance the ability to provide efficient aircraft engines well into the twenty-first century.

Engine Structural Dynamics and Aeroelasticity

The major problems in structural dynamics of aircraft propulsion systems center on an inability to predict accurately the vibration frequencies, patterns, and amplitudes of turbine engine and turboprop blading and the vibration behavior of the entire engine as an interacting dynamic system. The accurate prediction of blade frequencies is made difficult by complex, twisted, and swept-blade shapes, by strong centrifugal forces, by structural interactions between blades through the disks in which they are mounted, and by variations permitted by manufacturing tolerance. Engine system studies are difficult because of the large number of degrees of freedom involved and the presence of irregularly shaped components and of connections, such as bolted flanges, where the boundary conditions are difficult to specify and may be time-dependent and dissipative.

Thus, the study of propulsion system aeroelasticity embraces two major technical areas, both of which must be taken into account: structures and aerodynamics. The aerodynamics in concert with the structural characteristics effect the onset of flutter (of fan, compressor, and turboprop blades) and the nature of forced vibration of blades due to periodic variations in airflow.

Major increases in computer capabilities are making feasible the solution of the evolving complex, comprehensive structural, and aeroelastic theories.

Status Sustained vibration and large transient forces and deflections in propulsion system blading and in larger components such as shafts or casing parts can lead to fatigue failures and consequent loss of performance or of overall structural integrity. Hence, conditions that lead to sustained vibration or large transients must either be predicted in the design phase and avoided, or found and corrected in the development phase. Avoiding the high cost of fixing vibration and transient problems in the development phase is a major motivation for trying to improve prediction capabilities.

The avoidance of resonant vibration problems can introduce severe design constraints. Where prediction capability is not very accurate, overly conservative designs may have to be accepted, resulting in lower than optimum performance. For example, the avoidance of flutter is a controlling constraint on advanced fan and turboprop designs (controls, blade shape, and thickness). More accurate flutter analyses would permit the use of blade shapes that would give higher performance and lower noise.

For bladed disks that operate behind a set of stationary vanes in a turbine engine, it is essential that the lowest resonant frequencies of the blades do not coincide with any small-integer multiples of the shaft rotational frequency at cruise or takeoff conditions, since passage of blades into and out of vane wakes can set up resonant vibrations that lead to fatigue failure. Nonaxisymmetric inflow can yield similar problems in fans and turboprops. To avoid such interferences one must be able to predict the resonant frequencies accurately during design, or the blade shape must be altered after testing. Improvements in prediction accuracy have resulted from application of finite element codes such as NASTRAN, but further refinement is needed.

Fans and turboprops are subject to flutter that is induced by a steady airstream above some velocity. To predict the airspeed at which flutter ensues in order to ensure that the onset speed lies outside the flight envelope is a major aeroelasticity problem. Considerable progress has been made in the last five years, but more comprehensive theories must be developed.

The entire engine structure can undergo interactive deformations, especially due to transients caused by blade loss, hard landings, or sharp maneuvers. Further development of computer codes is needed to predict these deformations so that blade tip rubs, gas-path-seal wear and damaging bearing loads can be avoided by appropriate design.

Projections By the year 2000 blade frequency analysis will be accurate to better than 5 percent, taking into account all major types of modes including plate and shell modes and disk and shaft coupled modes; hence, it would be possible to design blading to avoid excessive resonant response to periodic flow variations. It also will be

possible to predict overall engine response to transient events such as blade loss, hard landings, and sharp maneuvers. By intentional introduction of blade "mistuning" and of damping materials and mechanisms, it will be possible to increase flutter speeds of fans, compressors, and advanced turboprops by at least 10 percent. Forced vibration levels will be reduced by 50 percent by such methods. A flutterfree, shroudless fan will be possible that has 1 percent higher efficiency because of cleaner airflow. Flutter prediction will include transonic, 3-D, and nonlinear aerodynamic effects in the analysis. It will be possible to predict flutter and forced response of counter-rotating turboprops as well as the interactions of such props with nacelles, pylons, and wings. Optimizer codes will be able to utilize accurate vibration constraints.

High-Speed Propulsion

A good case can be made for the advantage of speed in a variety of applications. Various trade-off studies have shown high potential for a ram/scramjet cycle in a launch system if the technology were available. Both strategic military and civil cruise aircraft of the future would achieve global ranges in several hours with hypersonic cruise speeds. For certain military missions, defense of the Navy fleet being one, very high speed is essential to success, and scramjet-powered missiles have been recognized as the most viable approach. In addition, speed can be vital to military vehicle survivability and can be traded with low observables in a mission effectiveness sense.

Status For flight Mach numbers above approximately 3.5, efficient compression of air ingested into an engine can be accomplished without turbomachinary (ram compression), and the ramjet engine cycle is preferred. For Mach numbers above 6, supersonic combustion (scramjet cycle) is required to minimize disassociation losses in the fuel combustor. Therefore, for efficient flight in the atmosphere above Mach 3.5, technology for ramjet and scramjet propulsion must be developed.

All operational ramjet systems have been designed for missile propulsion and have been highly specialized according to system and launch platform constraints. A systematic and sound ramjet technology base appropriate to a wide category of applications does not exist. There have been no operational scramjet systems to date, and the research has been at the basic technology level.

The critical technical issues for the extension of fundamental ram/scramjet technology involve the difficulty in achieving efficient fuel mixing and combustion in the very short residence times available in high-speed flows, and the associated inlet, nozzle, and vehicle-integration technologies that accompany high-speed flight.

Some important areas of activity in high-speed propulsion are discussed below.

Fuel Mixing in High-Speed Flows The resolution of the fuel-mixing problem is paramount for acceptable, high supersonic combustion efficiencies. Spatial and longitudinal distribution of the fuel is important to the overall mixing process and control of the heat release. The flow residence time in a given combustor length is basically a function of the flight speed and engine size. The combustor flow velocities typically could be about 2,000 feet per second at a flight Mach of 3.5 (subsonic combustion mode) and 6,000 feet per second for a flight Mach number of 8. This results in combustor residence times of a millisecond or less. The mixing and reaction process must be completed within these times.

Flameholding and Flame Stability Since the residence time is less for a small-scale supersonic combustor than for one in a large-scale engine, and since the ignition delay and reaction times are a function of pressure and temperature, small-scale research or missile-size combustors have flameholding and flame stability problems that are not expected in large engines. These must be circumvented in smallscale and must be researched in larger scale. The usual bluff body flameholders used as solutions in low-speed combustors are unacceptable in high-speed combustors because of the large performance losses that would be imposed at high combustor velocities.

Combustion Enhancement Techniques For lower flight speed (M = 3.5 to 4), initiation of the combustion process will require ignitors. As the flight speeds and combustor velocities increase, flameholding becomes a problem (especially for small-scale engines), and piloting may be required. Also, all other process times become critical, i.e., mixing, ignition delay, and reaction times. For liquid fuels, the additional times for droplet breakup and vaporization need to be avoided because of the resulting extensions to combustor length and weight. Combustion enhancement techniques such as pre-vaporization, preburning, or catalysts need to be considered.

Combustor/Engine Heat Transfer, Cooling and Thermal Protection Since at high flight speeds (M = 6 to 8) the stream stagnation temperature is already high (3000°F to 4800°F), the aerodynamic heating of the engine inlet and combustor surfaces is severe before the addition of 1,400 to 1,500 BTU per pound of air by the combustion process. For the combustor of a missile engine (life of one thermal cycle) flying at speeds up to Mach 6, very innovative use of advanced materials and structural design techniques are required to cope with the high internal pressures and heat fluxes. For ramjet/scramjets at Mach 6 and above with relatively long life requirements (reusable systems 1,000 to 2,000 thermal cycles) a regeneratively cooled structure is required for the entire engine with the combustor the critical component.

Inlet-Combustor Coupling In a ramjet/scramjet engine with fixed geometry (or minimum amounts of variable geometry) operating over a range of flight Mach number, the inlet tends to become sensitive to the combustor operation at the low end of the Mach number range. The degree of sensitivity depends on the throat areas (inlet and nozzle) and the fuel flow rate and heat release schedule. In order to maximize thrust for acceleration at low flight Mach numbers, definition of the limiting maximum fuel flow rate and heat release distribution for a given engine geometry without inlet/combustor coupling is necessary. Also, definition of the control parameters is required to avoid the limiting condition.

Inlet and Nozzle Aerodynamics For flight over a wide Mach number range, there are competing requirements for inlet performance. Typically, in the Mach 3.5 to 5 range, relatively low contraction ratios and high mass capture are desirable to start the inlet and accelerate, respectively. At higher Mach numbers and altitudes, higher contraction is required for efficient operation of the combustor. It is highly desirable to accommodate these competing requirements with fixed or minimally variable geometry; the payoff is in reduced system complexity and weight.

Efficiency in the nozzle is not as difficult as for the inlet. However, since the nozzle provides a substantial portion of the net thrust of the propulsion system, nozzle efficiency is quite important. In addition, chemical recombination losses can be substantial if the nozzle design is not appropriate.

Engine/Airframe Integration At flight Mach numbers up to about 4, the integration of the engine and the vehicle is desirable but not necessarily critical to performance. At Mach numbers of 6 and above, integration of the engine is essential. This occurs because the desired nozzle-exit to inlet-capture area ratios become large at such high Mach numbers, and the expansion cannot take place in an isolated nacelle due to excessive cowl drag. This leads to the use of the vehicle afterbody to accomplish the necessary expansion. In addition, the motivation to minimize engine size and weight suggests the use of the vehicle forebody to provide precompression for the propulsion system. Therefore, the engine and airframe must be considered together to achieve viable vehicle designs.

Projections A strong study and research program will be needed in priority areas including fuel mixing, flame stabilization, combustion enhancement, heat transfer/thermal protection, inlet and nozzle aerodynamics, inlet-combustor coupling, and engine/airframe integration to define and solve the critical problems associated with scramjet propulsion for the Mach 3.5 to 7 regime. A substantial data base will be generated; this will include ground demonstration tests of multiple-module hydrogen-fueled engine systems at angle-of-attack and yaw, and hydrocarbon engines on viable missile configurations.

Extensions of Mach 7 technology to Mach 10 to 12 would be achieved by projected advances in computational techniques and the utilization of well-designed experiments. For example, inlet geometries would be fully defined by CFD, and scaling laws for pressure/scale/velocity extrapolations would be generated. Nozzle aerothermodynamics will be controllable so that nozzle problems are not critically limiting. Regeneratively cooled structure, demonstrated at Mach 7, will be usable to Mach 10 to 12.

Very little is known about airbreathing propulsion for speeds beyond Mach 12. However, through careful study, analysis, and component-level experiments in the limited ground test facilities, it will be possible to define the problems and establish the potential for scramjet propulsion in this regime.

Ultimately, flight tests will be necessary to demonstrate airframe-integrated scramjet technology because ground test facilities are inadequate to test scramjet aircraft/propulsion systems at true flight simulation. By 2000, flight tests of hydrogen- or hydrocarbon-fueled scramjets would be made for both technology demonstration and for research.

Report of the Panel on

Structures

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STRUCTURES

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STRUCTURES

Introduction

Over the last 50 years, aeronautical structures have evolved from the wood, fabric, and wire of low-speed biplanes to supersonic aircraft fabricated with advanced metallic and nonmetallic materials. The advances made in structures technology have had significant impact on aircraft design and performance. An example is the large weight reductions being realized from the utilization of composite materials for secondary and primary structures. However, structural advances have been evolutionary, not revolutionary. Through the year 2000, there are opportunities to obtain significant new advancements in structural technology. These advances could result in considerable performance and capability payoffs such as increased payload, range, speed, maneuverability, fuel efficiency, and safety through reductions in weight, increases in strength, and the ability to make structures pliable. Also, with new manufacturing processes it is possible that reductions in production costs will be realized. Some of the structural technology areas where future major advances could be made are adaptive structures, thermal structures, damage tolerant structures, propulsion system structures, and new structural concepts.

The areas of structures research and technology that will enable future aeronautical vehicles to gain the performance and cost characteristics envisioned above are analysis and design (including an interdisciplinary approach), computation, testing, and data base management. In each of these research and technology development areas, there are many specific disciplines that require attention.

Of course, structures development is highly dependent on two other technologies--materials and fabrication. Advanced materials and related manufacturing techniques will be needed to create vehicle structures that will meet new mission requirements. Thus, materials and fabrication research and technology development is as important to the advancement of structures technology as structures technology itself. For instance, the development of the technology of metal-covered composites could have a major impact on the field of structures. However, the application of such large-scale composites will require development of new, efficient processing and fabrication methods and large-scale retooling, with its associated costs.

This report delineates the potential applications and payoffs for the five structures technology areas of special interest and identifies the technologies that could be developed to enable these payoffs to be realized. Table 3-1 presents a summary of the technology developments and associated payoffs for the five technology areas noted. The panel called special attention to the need for a new, full-scale facility for thermal structures studies. In addition, recommendations are made concerning the research direction and emphasis that would

TABLE 3-1 Structures Research and Technology Development for Aircraft in the Year 2000

Areas	Technology Developments	Payoffs
Adaptive structures	o Integrated analysis and design methods o Self-contained adaptive system (sensors-processors-high authority/bandwidth actuators) o Compliant materials	o Laminar flow control o Unconventional configurations o Safety o Load alleviation o Stability augmentation o Drag reduction o Maneuver augmentation
Thermal structures	o Advanced materials/coatings/finishes o Material characterization o Passive thermal protection o Fault tolerant active sensing thermal management systems o Advanced fabrication techniques o Advanced thermal-structural analysis	o Efficient load-carrying structure o Expanded flight envelope o Alternate fuels
Damage tolerant structures	o Onboard monitoring system o Nonlinear dynamic and failure analysis o Advanced tough materials o Energy-absorbing concepts	o Lower life cycle cost o Safety o Rapid repair o Extended adaptive structure o Extended time between inspections
Propulsion structures	o Aerothermoelastic and stochastic analysis o High-temperature/strength materials o Integrated construction o Advanced transmissions o Rotor/engine dynamics o Flaw tolerance	o Blended airframe-engine o 100% life increase o 50% increase thrust-to-weight ratio o 30% decrease in fuel consumption
Advanced structural concepts	o Advanced materials/processes/fabrication/repair o NDI/E o Damping augmentation o Noise attenuation o Integrated structure-engine ducting	o Unconventional configurations o Laminar flow control c Low cost/weight structure o Alternate propulsion systems

be required to advance structures technology for aeronautical vehicles for the year 2000 and beyond (see appendix).

Adaptive Structures

An adaptive structure is one in which a vehicle configuration automatically adapts its shape to obtain optimum performance throughout the flight envelope. A current example would be variable swept wings on fighter aircraft or control surface movements for load alleviation. This technology could be further advanced by allowing a wing to adapt its shape, conformally through continuous chordwise and spanwise variations, to maximize specified performance factors. This technology advancement could be realized through the development of highly compliant wing materials, embedded sensor/processor systems with high authority/high bandwidth actuators, and integrated analysis and design methods that would be used in the development and evaluation of designs. Adaptive structures also would include actively controlled landing gears, optimum blended wing/fuselage/engine inlet concepts, energy-absorbing structures for crash protection and control of airframe dynamic response, including flutter suppression.

Payoffs and Applications

Payoffs for adaptive structures would include the application of blowing and suction of air over surfaces and control of microamplitude traveling waves in wing skins to provide laminar flow for drag reduction. Aeroelastic tailoring of the structure can increase payload, maneuverability, and stability or reduce aircraft weight and size for the same payload/mission. Variable-geometry structures can provide mission-adaptive wings, with attendant favorable adjustments to weights, volumes, performance, mechanical complexity, and maintainability. Active leading and trailing edge devices, in conjuction with very flexible wings, can lead to tactical fighters with enhanced roll and turn rates at high dynamic pressures. Adaptive flutter suppression could result in the removal of flutter-placards (speed and g-load limits) for fighters with wing carriage of external stores. Active landing gear concepts contribute to NATO interoperability by providing U.S. fighter/transports with increased capability to operate on damaged airfields or airfields that have been rapidly repaired. Energy-absorbing structures can provide improved crash protection for transport and fighter aircraft passengers and crews.

Enabling Technologies

Achievement of these potential payoffs requires the development of ultra smooth, durable finishes and coatings; nondestructive inspection and repair procedures for sealed surfaces, including load-carrying ducting; development of high-strain, directional composite materials

with related joining and sealing concepts; and development and design of new actuation concepts and high-pressure hydraulic systems. Equally important will be the development of design philosophies, design/optimization and analysis methods, and data base management for the interdisciplinary treatment of aerodynamics, flight controls, and structures, and their dynamics. Continued efforts will be required to develop steady and unsteady aerodynamic prediction techniques and to maintain and develop experimental facilities for the adequate prediction of loads, flutter, and stability, particularly in the nonlinear regimes associated with high angle of attack and yaw, transonic speeds, and rapid rates of motion.

Flutter suppression for a wide range of stiffnesses, inertias, and flight conditions will be possible. This will require distributed sensors, fault tolerant architectures, high-authority/high-bandwidth actuators, adaptive algorithms, and onboard computation. Continued validation of design concepts, analyses in wind tunnels, and flight tests that duplicate both design and failed austere conditions are needed. Active landing gears and durable tires can move to the point where static and dynamic failure, stiffness, inertia, and damping of coupled hydraulic, pneumatic, and mechanical systems--particularly the development of mathematical models for large-amplitude, repeated motions--can be reasonably understood. These active controls require technology development through laboratory simulation and flight demonstration of necessary sensors, algorithms, and control devices. New nonlinear structural analysis methods are required for energy-absorbing structures.

Advances in a number of technology areas are required if the full benefits of adaptive structures are to be realized. Some of these advances are

- continued strong technology-base activities in ground loads; flight loads; structural and thermal analysis; vibrations; acoustics; unsteady aerodynamics; aeroelasticity; static, dynamic, and thermal test methods; fatigue; sensors; control algorithms, computation methods, and devices for active control; materials characterization; and the development of engineering data base management and distributed networking communications;

- interdisciplinary analysis methods, design methods, and communication of interactive design philosophies among aerodynamics, flight control, and structures; extension of current centers of excellence in aeroelastic testing to provide capabilities for interdisciplinary testing and certification;

- ground and flight validation of advanced structural concepts and interdisciplinary design to demonstrate the capability to design, fabricate, operate, and maintain adaptive structural concepts at acceptable costs; and

- development of durable and compliant material technology for adaptive and conformable vehicle shapes.

Thermal Structures

Structures whose designs are dictated by their operational thermal environment play an increasingly critical and indeed an enabling role in future supersonic aeronautical vehicles and for turbofan and jet engines. Following are some examples of the role of temperature in aircraft design: turbofan engine efficiencies for commerical transport aircraft increase with increasing combustion temperatures; supersonic cruise speeds of future commercial and military aircraft and missiles are limited by the elevated temperature strength and stiffness capabilities of engine and airframe materials; and the ability to develop reuseable flight systems powered by efficient high energy cryogenic fuels such as LOX/LH_2 depends on the development of flightweight tank and insulation systems with practical thermal cyclic life. Thus, it is clear that the development of the technology for aerothermostructural concepts that can have low weight and adequate life is critical to the success of future high-speed aircraft and cruise missiles.

Payoffs and Applications

Engine Structures

Turbofan and Turbojet Development of carbon-carbon, a relatively lightweight composite material which consists of graphite fibers in a carbon matrix, and durable ceramic structures for compressor components and engine liners would allow higher combustion temperatures. For example, carbon-carbon has potential for maintaining reasonable strength at temperatures above 1600°C but must be protected from reacting with oxidizing agents in combustion gases. The development of protective coatings is essential for providing long-life applications. Durable oxide ceramics, which are chemically resistant to oxidation, such as silicon-carbide fiber-reinforced lithium aluminosilicate glass have good thermal shock resistance for applications at temperatures of 1100°C and efforts to increase operating temperatures could provide healthy gains in the efficiency of engines. These materials also have potential for use in the design of lightly loaded hot airframe structures.

Ramjet At speeds above Mach 3.5, turbojet efficiency falls rapidly. At higher speed ranges, airbreathing engines that use ram air (ramjets) rather than compressors to compress the flow have better efficiencies. Hydrocarbon-fueled ramjet engine liners can reach temperatures exceeding 1700°C and require oxidation-resistant coating materials such as zirconia. Unfortunately, these coatings crack easily when

subject to thermal shocks. Structural concepts and/or thermal management procedures that result in ceramic applications with low thermal stresses must be developed before long life engine structures can be obtained. Possible use of cryogenic fuel such as liquid hydrogen would provide, along with a high combustion energy content, a heat sink that could be used as a regenerative coolant to moderate the engine structure temperatures permitting use of superalloys.

Scramjet Above Mach 6, ramjet engines require supersonic flow in the combustor for efficient operation. Diffuser wall temperatures exceed the capability of superalloys. Refractory materials must be used. Combustion temperatures exceed 2500°C, which is above the capabilities of any flightweight materials, and methods must be developed to keep combustor liners and combustor and nozzle structures to manageable temperatures. Ceramics with active thermal management procedures could provide the structural and thermal characteristics required.

These considerations suggest that any long-life vehicle that cruises at hypersonic speeds will in all likelihood be fueled by liquid hydrogen which will be used prior to combustion to cool regeneratively the scramjet engines and the airframe.

Airframe

Supersonic Cruise Cruise speeds above Mach 2 require airframe structures with load carrying capability above 140°C, which removes conventional aluminum alloys from consideration. New powder metallurgy aluminum alloys such as Ce-Fe-Al show promise for use at temperatures up to 250°C, corresponding to a Mach 3 condition. Graphite/polyimide composite materials, titanium alloys, and boron/aluminum and graphite/aluminum metal matrix alloys show promise for this application. These materials and related application technolgies could be available by the year 2000; however, for the latter material systems, much work is required to develop a strong data base and fabrication techniques for the designer. Above Mach 3, cruise vehicles must depend on advanced titanium alloys (such as 6-2-4-2 Ti) which has good creep properties to 450°C, approximately a Mach 5 cruise condition.

Hypersonic cruise Lightweight structures technology could be developed for flight at speeds above Mach 5, but would require external thermal protection or active means for cooling. For sustained hypersonic cruise where cryogenic fuels were used, the external metallic surfaces could be cooled using the heat sink capacity of the fuel, since the required insulation to maintain internal temperatures at reasonable levels may be heavier than the active cooling system.

Transatmospheric Flight For short-duration flights to the upper atmosphere, superalloy materials can be used where skin temperatures reach 1000°C. With reentry temperatures reaching equilibrium radiation at higher levels, durable thermal protection systems using superalloys or carbon-carbon can be developed to protect the load-bearing structure. Carbon-carbon has the potential for use as a reusable thermal protection system at temperatures exceeding 1400°C, but would have limited life without development of improved oxidation-resistant coatings. At high-radiation-equilibrium temperatures, disassociated gases in the upper atmosphere recombine at metallic surfaces releasing heat and raising surface equilibrium temperatures. Noncatalytic coatings could be developed to provide surface protection for thermal protection systems. Leading edges of reentry vehicles, where temperatures can approach stagnation temperatures, are particularly susceptible to rapid erosion when made of ceramics or carbon-carbon and should be fabricated using superalloys. However, such designs require active thermal control procedures to keep skin temperatures within the safe operating range of the material. Transpiration cooling or high-temperature heat pipes technology could be developed to remove the heat loads and reduce temperatures.

Enabling Technologies

Fuel Tanks Cryogenic fuels will embrittle most flightweight material systems with the exception of some aluminum alloys. A great deal of experience in the application of flightweight aluminum cryogenic fuel tanks has been attained in the space programs; in all cases, however, tanks were built for single flights, and no experience is available that establishes the long-term fracture characteristics of tanks continually cycled between cryogenic and elevated temperatures. Such experience could and must be obtained before liquid hydrogen fuel can be used for reusable hypersonic or transatmospheric vehicles. As tank radius increases, the wall membrane stresses increase proportionately. If filamentary composite materials with an aluminum matrix can be shown to resist hydrogen embrittlement, their high strength density could offer considerable weight savings over conventional aluminum tanks. For reusable tanks, efficient lightweight tank insulation, necessary to retard fuel boiloff, could be developed along with an effective insulation/tankwall adhesive that can withstand continual thermal cyclic loads.

Thermal Protection Systems High-speed cruise and transatmospheric flight systems subject to high heating rates during reentry are likely to require external thermal protection systems that are suited to all-weather operation. The current system, used on the space shuttle, has relatively delicate radiative heat shields of ceramic tiles with excellent thermal characteristics, but with low strength and poor water absorption resistance and durability. Some materials have been shown to be weight competitive with the ceramic insulations but have

not as yet been qualified for flight, such as metallic thermal protection systems with durable surfaces, e.g., Rene 41, Inconel 617 superalloys, coated Cb and Ta refractory metals, Ni- and Fe-based oxide-dispersion strengthened alloys, and nonmetallic carbon-carbon composite materials coupled with internal efficient fibrous insulation. These materials also have potential for use as hot load bearing structural components because of their high strengths at elevated temperatures. However, they are difficult and expensive materials to fabricate. Procedures to improve forming and welding while maintaining the mechanical characteristics of the materials would have to be developed.

Thermal/Structural Analysis Most structural analyses of complex configurations are performed using finite-element procedures, while most thermal analyses are still based on lumped mass discrete analysis procedures. More emphasis could be directed toward the development of finite-element thermal analysis procedures that interact directly with structural finite-element models using interpolation schemes. Solution methods could be reformulated to take advantage of the expected future computational capabilities that will allow parallel, multiple processing. Active thermal management analysis techniques could be coupled with control laws and thermal stress analyses to provide for the design of adaptive thermal structures controlled by embedded computers that actively adjust thermal stresses and deformations during operation by sensing and controlling critical conditions through adjustment of heat flow. Progress also is anticipated in the analysis of aerodynamic laminar and turbulent boundary layer heat transfer for complex configurations such as thermally bowed heat shields.

Advanced Materials Composite materials with refractory fibers embedded in superalloy or refactory metal matrices, durable composite ceramics, and hybrid carbon-carbon materials should have great potential for high-temperature applications. However, it is expected that it will require some 8 to 10 years of developmental research and characterization work, after laboratory developmental research is completed, before the designer will be able to use these advanced materials for flight systems. Thus, it is suggested that most of the "new" material based systems in operation in the year 2000 are now in development in the laboratory.

Damage Tolerant Structures

An aircraft structure should be capable of performing its mission even though it may possess various types of inherent or induced faults. Imperfections introduced during fabrication and normal operation are accounted for in a proper design by appropriate strength margins, quality control procedures, and in-service inspection techniques. Other damage occurs because of abnormal phenomena such as overloading due to

explosive bursts, gusts, hard landings, and impacts due to projectiles, flak, and birds. In addition, deterioration of the structure can occur due to unexpected material corrosion or cracking, as well as improper ground handling. Clearly, the abilities to determine the extent of the damage, to evaluate the residual structural capability, to repair the damage, and even to operate safely with latent damage are desirable features of damage tolerant systems.

The technology that could be developed includes a broadening of the usual definition of damage tolerant structures to include overloading and combat damage from ballistic and radiation sources and the design and repair of the "new" structures at acceptable costs and weights. The topics range from providing materials with high toughness to understanding crack growth in 3-D structures to providing detailed design and fabrication procedures that minimize stress concentrations and corrosion.

Payoffs and Applications

Damage-tolerant structures can directly influence the life cycle costs of new aircraft through extended fleet inspection intervals and by reducing inspection and repair equipment needs and skills. They have the potential to tolerate better increased operating strains associated with changes in mission requirements. Improved damage tolerance can provide better combat survivability to ballistic impacts and radiation exposure while simplifying related repairs, thereby providing an effective force-multiplier.

Enabling Technologies

Enabling technologies would include high-strength and high-stiffness materials with the required toughness; the understanding of failure mechanisms, crack growth, and residual strength in highly loaded, 3-D structures; the accurate prediction of nonlinear flight and ground loads and internal stresses for extreme operating conditions; the development of portable nondestructive test (NDT) equipment and rapid procedures for inspection of internal structure; the understanding of ballistic and radiation damage; the development of rapid, integrated thermal/structural analysis methods for preliminary design; and the development of low cost structural repair procedures, tailored to mission and economic life.

Propulsion

Propulsion systems have evolved over the years from simple piston engine driven propellers to current high thrust turboprops, fans, and jets. As these current systems continue to evolve, they will be

joined by advanced turboprops that utilize highly swept and loaded propellers and eventually by hypersonic cruise ramjets. The range of environments incurred by these engines will be extremely diverse, ranging from conditions of transonic 3-D flow for advanced turboprops, stoichiometric temperatures in turbojet engine hot sections, and temperatures above 3000°F for hypersonic ramjet/scramjet engines. For these engines, propulsion system structures must be durable and compatible with high temperatures to provide high propulsive efficiency and low aircraft weight.

Payoffs and Applications

An achievable goal of propulsion systems structural research through the year 2000 is to contribute to the development of engines that are 25 percent more efficient than comparable current propulsion systems, require 50 percent less design and development time, have a 50 percent increase in thrust-to-weight ratio, and a 100 percent longer life.

In the case of turboshaft and turbofan engines, hot gas temperature will reach stoichiometric levels in an effort to increase efficiency. Supersonic cruise turbojets (Mach 3) will see similarly high temperatures in the combustion section and nozzle as well as temperatures of over 1000°F (524°C) in the high pressure compressor. Hypersonic aircraft will be designed to blend airframe/ramjet, and peak skin and engine temperature will be over 3000°F (1635°C). Candidate materials include ceramics, metal matrix composites, high-temperature nonmetallic components, and super alloys. Active/passive thermal protection systems technology will have to be developed for these high-temperature applications.

Enabling Technologies

Critical to the development of durable, lightweight, highly efficient engines is the need to utilize properly each material in the structure of the engine. In the major engine structural elements, the strength and durability of components must be tailored to "optimize" design and performance, requiring the use of different materials. These requirements will become even more stringent as inlet air temperature increases and peak hot section temperatures rise. The optimal arrangement may well be through the use of hybrid components fabricated from different materials to fabricate larger integrated engine structures such as fully bladed disks. Currently, this technology does not exist. However, the capability could be developed by the year 2000.

Another key supporting technology for this class of development is a better understanding of the dynamics of integrated rotating systems. Current technology does not address adequately this design issue for

highly loaded flexible systems, but technology could be developed by the year 2000.

In new structural materials, increased tolerance to flaws will improve safety and durability. This capability is of increasing importance as high temperatures and performance levels increase, and could be realized with appropriate research and technology development by the year 2000. Flaw tolerant materials will result in lower-weight structures resulting from less conservatism in design.

To realize more fully the benefits of advanced materials and structural designs, development of interdisciplinary analyses techniques that can treat engine-related aerodynamics, structures, and thermal and dynamic effects concurrently is required. This means that the analyses must address matters ranging from hot structures such as turbine stages, to aeroelasticity of advanced turboprops and swept fans. Current technology tends to address the aerodynamics, thermal, and structural matters analysis separately. Significant progress can be made in this area of aerothermostructural analysis with appropriate effort so that the goal of higher-performance, lightweight, efficient, and durable engines can be achieved.

Advanced turboprops can provide fuel savings of 30 percent relative to today's turbofan engines with the potential for an additional 20 percent by the year 2000. These high-performance turboprops will entail the use of swept fans. However, swept fans present several major technology problems related to understanding and modeling the aeroelastic structural dynamics and the aerodynamic performance of swept multibladed cascade systems. It is projected that by the year 2000, transmissions capable of carrying over 20,000 horsepower will be needed for large, advanced turboprop aircraft and over 50,000 horsepower for geared fans in very high bypass ratio turbofans. Similar types of transmissions also will be required for large rotorcraft; however, such transmissions will involve much larger speed reduction and, therefore, much higher torques than will be experienced on the large turboprop aircraft. In particular, technology would be advanced so that there is the potential to reduce associated power loss by half through new gearing and drive system concepts. Materials and structures technology developments play integral roles in the achievement of these capabilities. Here too, it is believed that the potential can be in hand with application of resources.

An additional area of enabling technology for the advancement of structural research in propulsion systems is stochastic analysis. In the harsh structural environments anticipated in engines by the year 2000, loads prediction, and knowing the physical state of the material systems will be crucial to evaluating the strength and durability of major components. However, thermal and pressure loads are not steady in time or space, and the physical state of components dependent on current and past conditions will not be known exactly. Non-deter-

ministic analysis methods could be developed to help predict loads and to help construct constitutive behavior and structural models for stress/strain/deformation analysis.

In summary, the major areas for structures research that can assist appreciably in enabling aeronautical propulsion systems to increase efficiency, performance, and durability significantly by the year 2000 are high-temperature materials structural applications; hybrid material concepts that allow highly integrated components; flaw tolerant structures; coupled aerothermostructural analysis (including aeroelasticity of advanced turboprops and swept fans); compressor and turbine rotor dynamics, including forced response; high-power, light-weight transmissions; and stochastic loads and analysis methods.

Advanced Structural Concepts

By the next century, many aircraft will have structural configurations that are very different from those being used today. These new arrangements will be developed in response to intensified requirements for low weight, low cost, and low maintenance, as well as the need to respond to new design concepts in the aerodynamic, control, and propulsion disciplines, such as adaptive structures, laminar flow control, and airframe and engine integration. For these structures there will be integral construction, reliable use of brittle materials, tailored structural properties, energy-absorbing structures, and articulated (variable geometry) structures.

Payoffs and Applications

The payoffs arising from research and development of the technology in advanced structural concepts fall into two classes: enhancement of merit parameters such as weight and cost; and those in support of advances in other disciplines such as laminar flow control.

The use of advanced structural concepts would produce the following quantitative payoffs through the following reductions: weight by 30 percent; fabrication cost of commercial and general aircraft structures by 30 percent; and man-hours for structural inspection and maintenance by 50 percent. In addition, new structural arrangements will enable the following types of technological advances: adaptive, actively controlled structures; very high aspect ratio wings; laminar flow control and reduced turbulent flow drag; and novel aircraft systems such as multibodied or wing-tip-coupled aircraft. Application of the new structures technology will contribute significantly to both enhanced conventional aircraft performance and reduced costs, but will also make possible new classes of aircraft and services.

Enabling Technologies

To achieve major advances in integral construction, the important technologies include joining techniques of brazing and seam welding for metal structures and those of ultrasonic welding and bonding for composite metal-composite hybrid structures; and large-scale, precision integral casting, forging, and extrusion. Advances in these areas will reduce significantly the machining required to produce finished metallic structures. Similarly, large, intricate layups and advanced pultrusion capability will enable the production of efficient, large composite components.

Integral construction usually is accompanied by a loss of internal damping and the natural crack stoppers furnished by mechanical joints. Consequently, research must be performed on appropriate damping augmentation techniques and crack-growth suppression if effective use of integral construction is to be made and dynamic, fail-safe problems avoided.

In the future, materials formed by rapid solidification and powder metallurgy, from metal-matrix and carbon-carbon composites, and from ceramics can be available. Research and technology development directed at structural configurations is needed to take advantage of the increased capability of these materials while accounting for such factors as decreased ductility and toughness. Also needed is improvement in design/analysis methods to assure critical areas are identified during design process.

Flaws become of greater concern as structural and material efficiency is increased. Consequently, research is needed on nondestructive methods for locating flaws and techniques for characterizing those that are dangerous. In addition, repair methods need to be developed so that inhibiting imperfections can be removed.

Cost is a prime concern, particularly for commercial aircraft. Work is needed on fabrication techniques that will reduce significantly the cost of manufacturing, testing, and inspecting, especially with respect to composites. Examples of manufacturing that need to be developed are techniques for rapid layup of the component, nonautoclave curing, and the ability to construct major components through filament winding. If room-temperature-curing polymers can be used, large savings in energy are possible.

Noise attenuation becomes more important as power and performance increases. Research is needed on structural arrangements designed to achieve good acoustic control without increasing weight and cost.

Boundary layer control will continue to be a profitable technique for achieving increased performance. From a structural viewpoint, the maintenance of laminar flow entails very smooth surfaces. Today's

fabrication techniques are good enough to meet smoothness requirements. However, more has to be known about maintaining the surface quality in service. Boundary layer suction is another and more effective way to maintain laminar flow and delay transition to turbulent, drag-producing flow. Suction requires porous wing skins and ducting behind the skin. Weight penalties can be avoided only by making the surfaces and ducting load-carrying structural components. Work is needed to understand and develop design approaches to the required functional integration.

This class of work in advanced structural concepts depends on building and sustaining a good analytical and design capability. Pursuit of this activity should be able to provide much of the technology identified for application by the year 2000.

Structural Analysis and Design Technology

It is reasonably clear that by the year 2000, significant advances in structural analysis and design in four major technical areas can be made. These elements, summarized in Table 3-2, are advanced analysis methods; multidisciplinary analysis and optimization; life prediction; and material characterization. The future design and analysis environment will be one in which there is less reliance by the designer on historical design information to achieve advanced vehicle configurations. It is postulated that accurate and efficient analytical and testing methods will allow advanced configurations to be evaluated properly during the design and development process. This effort will not only encompass the traditional single discipline approach, but allow integration and optimization of the various technical disciplines.

Advanced analysis methods along with an understanding of material failure mechanisms will provide the capability to reduce design and test time, saving costs associated with the development of new structural designs. Figure 3-1 illustrates the current path and the path required for future structural analyses. If the new capability is to be available for aircraft developments for the year 2000, work on development of the new tools must continue and be given priority. The goal of a global integrated analysis capability is presented in Figure 3-2. This shows that new technical disciplines are required to develop, in a cost-effective way, the projected high performance and expanded mission vehicles of the future. The development of new theoretical concepts and the use of future computational technology, including artificial-intelligence-based expert systems, will be required. A major concern is how to develop formal methods to interface and exchange information between the traditional discipline areas, including possible organizational changes.

TABLE 3-2 Structural Analysis and Design Research and Technology Areas

Technical Area	Payoff
Advanced analysis methods	
o Hybrid analysis	o Reduce development and testing costs and time
o Adaptive methods	
o Symbolic computation	o Evaluate advanced structural concepts
o Stochastic loading and analysis	
Multidisciplinary analysis and optimization	
o Integrated analysis	o Increase efficiency, performance and durability of entire vehicle system
o Optimization methods	
o Sensitivity analysis	
Life	
o Life prediction theories	o Increase life, safety, reliability and reduce costs
o Failure theories	
o Damage/defect analysis	
Materials characterization	
o Constitutive relations	o New materials for severe environments
o Material damping	

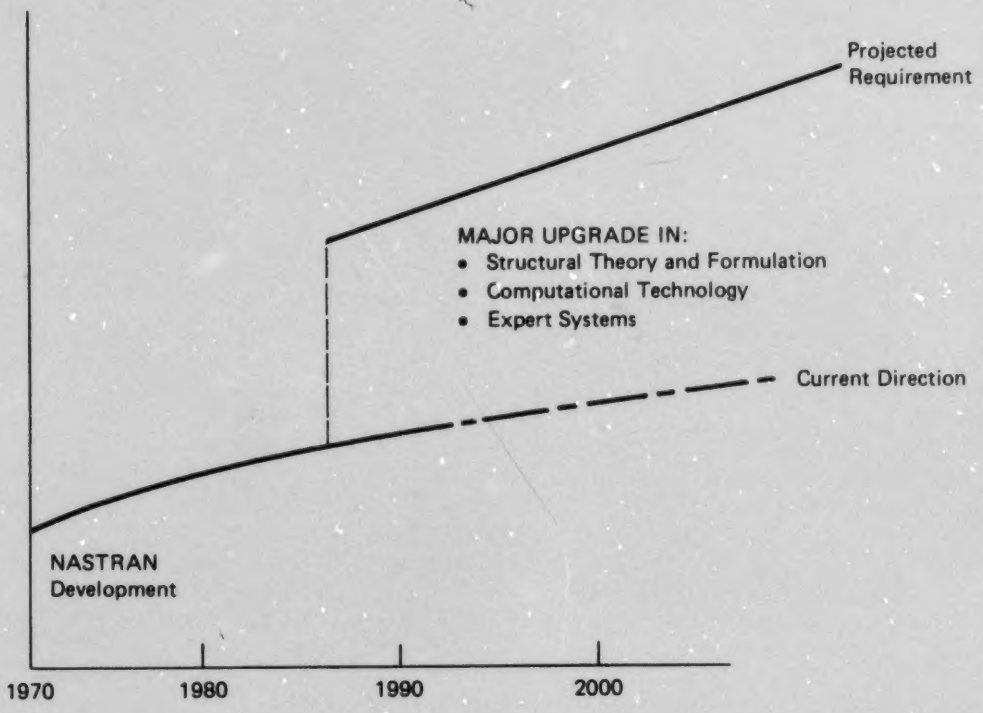

Figure 3-1 Projected Directions for Focused Structural Research

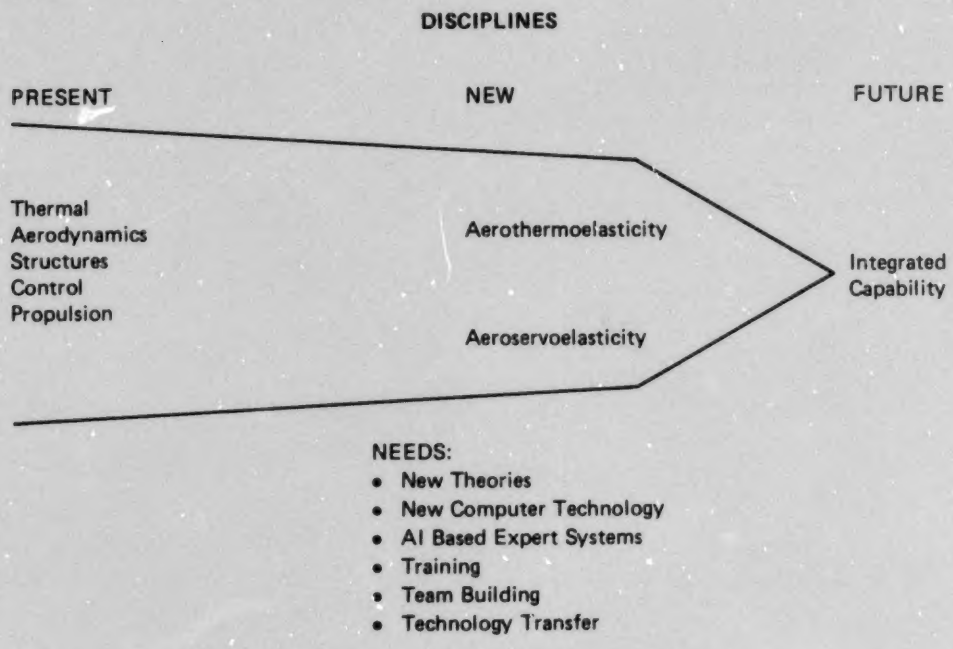

Figure 3-2 Projected Direction for Analysis and Design Technology 88.

As has been noted, present structural analyses are based on the finite element method, developed over the last two decades. This method has been incorporated in medium and large software systems designed to solve various classes of linear and nonlinear problems. However, the method is not ideal for many of today's and certainly not for future structural design problems. Nonlinearities associated with high-temperature structures, large deflections of very flexible structures, 3-D stress conditions, and uncertainties in loads and material properties comprise the greatest challenges. By the year 2000, all of those factors will have to be dealt with accurately and efficiently. Specific areas for analytical advancement, offering the possibility of solving the most difficult aeronautical structural problems are hybrid analysis, adaptive methods, symbolic computation, and stochastic analysis.

Hybrid analysis refers to different analytical and/or numerical procedures embedded in a complete solution strategy. An example is the combining of different numerical discretization procedures (e.g., finite element and boundary integral techniques) with direct (global) variation methods at the problem level into a single hybrid technique to model a complex structure subjected to severe operational conditions. Such procedures combine advantages from the two parent techniques and can result in significant improvement in computational efficiency and accuracy.

To utilize these advanced methods, adaptive analytical methods must be developed. Currently, adaptive methods deal mainly with automatic time and load stepping, along with methods for controlling displacement increments. Adaptive mesh generation and refinement methods for finite element analyses are being developed as well as new convergence and automatic element selection criteria. The opportunity exists to extend adaptive methods for selecting the degree and type of interpolation function and type of integration scheme for advanced finite element analysis. This also can be used to develop automatically best-fit hybrid methods of analysis for selected substructures and can adjust the process for dynamic load conditions.

A powerful technique for advanced analysis is symbolic computation. Symbolic manipulation has been used primarily in an "open-loop" manner to reduce the amount of "paperwork" needed to conduct specific analyses or to develop specific methods. With this technique, exact analytical calculations can be performed for many problems in place of numerical approximations. Systems of equations can be manipulated explicitly, reducing the time required to automate the entire adaptive development process.

Another area that will be of much greater importance by the year 2000 is stochastic (or probabilistic) analysis. This form of analysis has been used for many years to describe aerodynamic loads, determine the vibrational response of aircraft structures, and estimate the

effects of damage and other structural imperfections. Projected aircraft developments will require analysis of more complex systems operating over broader ranges of flight conditions than those at present aircraft. Factors such as complex materials and structures, high temperature structures, and plastic strain will have to be dealt with. These factors require analysis methods that account for the spatial and temporal variations in loading conditions and material states throughout the structure. Although deterministic analyses will still be used for structural analyses by the year 2000, more emphasis will be needed on probabilistic methods to account for thermal-mechanical uncertainties throughout the aircraft structure.

Important design constraints are imposed by aerodynamics, heat transfer, controls, and materials on the structural design. These and other constraints on the structural design will establish the geometric configuration and thermal-mechanical limits to which the vehicle will be constrained. Today, interdisciplinary interactions between structures and other technologies are handled largely on an iterative and sequential basis. The analysis methods for the various disciplines can differ significantly. Most structural analyses are performed using finite element methods while heat transfer and fluid mechanics analyses generally use finite difference methods. Often, there are analytical incompatibilities that make interdisciplinary analysis difficult. There is a need to develop design procedures that allow the integrated analyses of combined technical specialties to establish and evaluate more effectively design constraints among the various technical disciplines.

An extremely important tool for integrated multidisciplinary analysis involves optimization methods, along with advanced data management capability. Current advances in nonlinear mathematical programming and computational technology will allow the vehicle design to evolve toward an integrated process that incorporates various discipline constraints, including overall system performance goals. The ability to manage efficiently the flow of design information in a distributed computational environment is a key requirement for integrated, multidisciplinary analyses.

The need for life cycle analysis in aeronautical structures has been required from the time of the earliest aircraft. However, even with the intensive research over the past few decades, a considerable degree of conservatism still must be built into aircraft structures. By the year 2000, advancing aeronautical technologies would allow more definitive analysis of structural life cycles. This will include, of necessity, the effects of failure and damage/defects and appropriate materials characterization. The latter includes determining accurate constitutive relations for the materials to be used especially for high temperatures, and knowledge of such matters as mechanisms for damping.

Computational Technology

Development of computing systems by the year 2000 will have a significant effect on almost all aspects of the structures discipline. The developing hardware and software technologies that are likely to have the strongest impact are summarized in Table 3-3 and are discussed here briefly.

Small Systems

These include both new powerful microprocessors and engineering workstations.

Microprocessors and Chip Technology The trend of increasing the number of devices packaged on a chip has resulted in substantial opportunities for miniaturization and increases in speed of microprocessors and minicomputers. Two major research efforts are currently underway for improving the processor speed, VHSIC (very high speed integrated circuits) and VHPIC (very high performance integrated circuits). The first is supported by the U.S. Department of Defense and the latter by the United Kingdom. The powerful chips resulting from these efforts could be used as parts of onboard monitoring and control systems that have such functions as augmenting stability, reducing loads, improving ride comfort, and minimizing aerodynamic drag, thereby allowing more effective, economical designs. Other monitoring systems for the detection, recording, and evaluation of stochastic damage could support service requirements, increasing the mean time between inspection.

Microcomputers are likely to become an integral part of laboratory testing for processing data in support of direct vehicle certification. This would permit hybrid analysis/test methods to be developed and applied to complex operational load test simulations.

Engineering Workstations With Simple User Interface Engineering workstations using very large scale integrated circuits (VLSIC) 32-bit processor chips and having over 16 M bytes (or more) of addressable memory have been developed. It is anticipated that the workstations that could be developed by the year 2000 would be desktop computers with sustained speeds of 1 billion FLOPS and over 50 M bytes of addressable memory. Moreover, sophisticated, easy-to-use software and hardware interfaces could be developed that will improve the productivity of the engineer. Future options are likely to be multiwindowed, controlled by voice or hand-held pointer. These devices would reduce substantially the analysis and design time while improving the accuracy of solutions to complex design problems.

TABLE 3-3 Computational Technology Development

Technical area	Payoffs	Requirements
Small systems		
o Microprocessors (VLSI, ULSI, VHSIC, VHPIC)	o Onboard monitoring of life, damage, and stability o Ground test systems	o Software development
oEngineering workstations	o Increased engineer productivity	o Software development o Training
Computer architectures		
o Supercomputers, highly parallel computers	o Handling broader range of complex problems (e.g., stochastic modeling)	o New computational strategies
o Distributed computing and networking	o Multidisciplinary analysis and optimization	o Parallel analysis and optimization algorithms o Software development
Software		
o AI-based expert systems	o Aid in selection of appropriate model and algorithm o Aid in the analytical formulation	o System development o Software development o Integration of analyses modules
o Data base management systems	o Improved interdisciplinary coordination	o Integration of structures with other disciplines

New Computer Architecture

Increased computer performance can be obtained using either single or a few high-speed processor(s), or several (thousands of) inexpensive processors. These two classes usually are referred to as supersystems and highly parallel systems, respectively. The development of supersystems now spans two generations. Future supersystems are expected to have a sustained CPU speed in excess of a trillion floating point operations per second. These supersystems will make possible new levels of sophistication in structural modeling, as well as in problem depth and scope that are not possible today. Examples are large-scale multidisciplinary analysis and design problems and reliability-based (stochastic) modeling.

Highly parallel systems could expedite substantially the design process by allowing the designer to carry out analysis and design tasks in parallel. This will allow efficient solutions to integrated structural and other discipline problems that cannot be solved today.

Distributed Computing and Networking

The future computer hardware environment can be characterized by an array of computer hardware capabilities tailored to individual subsets of the total system or facility. The hardware could range from the core capability of supercomputers that provide large-scale computations outward to periphery systems that consist of a wide variety of workstations for moderate-scale interactive user interface/control and calculations.

The array of computers could be interconnected into local or long-range networks. Local networking can facilitate cooperative multidisciplinary investigations and design among team members interacting through shared data bases. Special software would be available to allow programs to migrate from one hardware environment to another. Inexpensive long-range networking can have several significant effects. Issues of proprietary data could be reduced by sending the program to the location of the owner of the proprietary data, performing the computations there, and receiving only the processed nonproprietary results.

Artificial-Intelligence-Based Expert Systems

Artificial-intelligence-based expert systems, incorporating the experience and expertise of practitioners, have high potential for structures design applications. Such systems could aid the engineer in the modeling of the structure, the adaptive refinement of the model, the selection of the appropriate algorithm and procedures to be used in the solution, and the evaluation of analysis results. Expert

systems also could aid the designer by freeing him from such routine tasks as the development of process and material specification.

Large Data Management and Data Base

Future engineering software systems are likely to have the basic analysis software (such as data storage and control) as part of the software infrastructure and the discipline specifics (such as the finite element properties of structural components) as part of the application software. Advanced data base concepts would provide improved interdisciplinary coordination and facilitate the integration of structures programs into CAD/CAM systems. This requires the development of large-scale data base management systems for distributed heterogenous computer networks.

The aforementioned list of potential advances and trends in the computing technology is by no means complete or exhaustive. But these developments promise to have the greatest beneficial impact on the development of aeronautical structures technology.

Testing Technology

Testing technology is comprised of five major technical areas: (1) hot structures and cryogenic tankage, (2) constitutive behavior, (3) flutter/flight loads, (4) propulsion system dynamics, and (5) nondestructive evaluation and inspection. These areas are critical to structural technology readiness for new aircraft development. Table 3-4 lists the areas as well as their potential applications, related gains, and implementation requirements including test facilities.

Hot Structures and Tankage

The hot structures/tankage and thermal management test technology activity would permit validation of structural concepts for high-speed vehicles and ramjet/scramjet engine applications. Two different types of facilities would be required for the development of pertinent technology: (1) a flow facility to evaluate aerothermal conditions, and (2) an environmental simulation test facility to assess structural components subjected to combined mechanical/thermal loads under vacuum. The flow facility, with capability to Mach 10, would include the development of techniques for the measurement of high temperatures. A new facility does not appear to be required. Modifications to the existing 8-Foot High Temperature Structures Tunnel at NASA's Langley Research Center would provide this capability.

The only large static thermal structures test capability in NASA exists today at NASA's Dryden Flight Research Facility. This facility

TABLE 3-4 Structural Testing Technology

Technical areas	Target application	Payoff	Requirements
o Hot structures/ thermal management	o Hypersonic vehicles	o Aircraft/missile concepts greater than M 5	o High-temperature instrumentation
o Cryogenic tankage	o Transatmospheric vehicle o Heavy lift launch vehicle	o Validated ram and scramjet engine structures o Application of new high-temperature materials (greater than 2000°F)	o M5 - 10 full-scale component test facility o Integrated thermal/ structures test laboratory with reduced atmosphere control
	o Ramjet/scramjet	o Passive/active thermal management methods o Integrated airframe/ tankage/engine concepts	
o Constitutive behavior of materials	o High-temperature materials	o Improved analytical modeling capability	o Multiaxial test methods
	o Composites	o Life prediction	o Hybrid analysis/test techniques
	o Advanced metallics	o Identified failure mechanisms	
o Flutter/flight loads	o Advanced fighter	o Validated integrated analysis methods and load alleviation concepts	o Complex model high Reynolds number wind tunnel tests
	o Transport aircraft	o Verified 3-D unsteady aerodynamics	o Advanced surface control mechanisms
	o Hypersonic vehicles	o Real-time measurement of steady/unsteady loads o Improved vehicle perfcrmance	o Research flight tests

TABLE 3-4 Structural Testing Technology (continued)

Technical Areas	Target Application	Payoff	Requirements
o Propulsion system dynamics	o Jet engines	o Validated dynamic/flutter analysis methods	o Multistage engine dynamics test facility
	o Turboprops	o Reduced dynamic response in engine structural components o Turboprop structural verification	
o Nondestructive inspection and evaluation	o Advanced vehicle configurations	o Efficient structural design concepts o In situ damage assessment	o Reliable test methods for closed sections o In situ sensor/processor capability and damage assessment methods

has the capability to test large structures such as a wing box under mechanical loading and thermal loadings up to about 1800°F. A new test capability is required that could test instrumented structural components under combined mechanical/thermal loads with reduced atmosphere and temperatures approaching 3500°F. This facility also would permit tests and evaluations of passive and active thermal management systems, such as heat pipes, under combined thermal and mechanical loading cycles. This technology development tool is a prerequisite for the design and development of aircraft and missiles that operate at very high speeds. This capability would support directly the broad-based research program in thermal structures previously discussed. Of course, this facility would be used to develop and validate techniques for integrated thermal-structural analyses.

Behavior of Materials

Understanding fundamental material characteristics and responses to various types of loadings and conditions represents a major challenge to the structural analyst. Material constitutive relationships are developed from test data and used in structural models failure mechanisms and to predict total life times for structural components. A major problem today is the development of models to represent this class of design problem, particularly for high-temperature effects. The development of multiaxial coupled test and analysis methods for material characterization under actual, real-time load conditions for structural component evaluation is needed. This capability does not exist, but would be a valuable asset in the development of advanced aircraft and engines.

Flutter/Flight Loads

The area of aircraft flutter and flight loads evaluation could benefit from the development and validation of a broad range of discipline-oriented analytical methods that treat subjects ranging from unsteady aerodynamics, controls, and structural dynamics and integration of these analyses for system optimization. A comprehensive test program in flutter/flight loads that includes wind tunnel testing through flight testing is also critical to the advance of the technology.

The adaptive structures research thrust, previously discussed, will require extensive testing to develop and validate new structural configurations where control of aeroelastic response is exercised. Important here would be the capability to analyze real-time coupling during flight tests. This would permit the incorporation of actual components that are difficult to properly model, such as an adaptive surface

control mechanism, with analysis methods to evaluate safely and accurately new concepts for flutter and flight loads control.

Propulsion System Dynamics

Turbine engines and advanced turboprop configurations present challenging structural dynamics/flutter problems. The capability to analyze effectively this class of problem is constrained severely by current analysis capability. Moreover, available test facilities do not allow complete dynamic and forced response testing of turbine engine or turboprop configurations. A new facility for full-scale engine and turboprop dynamic testing would provide the appropriate enhancement of the structural dynamic technology data base for these advanced propulsion concepts and assist in the validation of new analytical methods.

NonDestructive Evaluation and Inspection

Methodologies are required to help assure the effective, safe use of new material/structural concepts, such as for closed sections (i.e., hat stiffeners and sandwich structure) that will be utilized in advanced vehicle designs. A limitation to the use of advanced structures is concern over detecting improperly bonded joints, local damage or cracking, and other types of manufacturing defects. Internal corrosion in areas not readily observable is another concern.

Improvements in nondestructive evaluation and inspection will allow the designer to utilize more efficient design concepts, but they still must consider damage tolerance and its assessment. Advanced design concepts could benefit from and may require in situ damage assessment sensor/processor capability. This could provide a lifetime assessment of component integrity and information concerning repair or replacement needs.

The five test areas discussed could provide important enabling technology for advanced aeronautical vehicle development. The hot structures and engine structural dynamics test areas dealt with indicate the need for new facilities to support the development of advanced technology. The flutter/flight loads test area facility need could be satisfied through the utilization of existing facilities. Flight research appears to be an integral part of the future facility picture.

Report of the Panel on Materials

Russell J. Diefendorf, Panel Leader
Salvatore J. Grisaffe, Rapporteur

MATERIALS

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MATERIALS

Introduction

Materials and manufacturing technology are critical to advanced aircraft and permeate all disciplines. Current aircraft systems employ a variety of materials--each selected to provide the best vehicle design in terms of performance, safety, reliability, manufacturability, and life cycle cost. However, a mistake in materials selection could bankrupt an airframe or engine manufacturer.

Thus, the introduction of new materials is a slow process. Generally, new materials are used initially in noncritical components until their performance in service can be confirmed. Then, as confidence grows, they are used in more and more critical applications. Finally, if appropriate, new materials are used in critical, static elements and then in dynamic components. Thus, because the nominal time for development of a conventional monolithic material ranges from 5 to 10 years there is a 10- to 15- year lag between laboratory effort and introduction into service. Therefore, to assure the availability of materials suitable for production aircraft and engines in the year 2000, the concepts already must have been identified and must be progressing along evolutionary paths toward application.

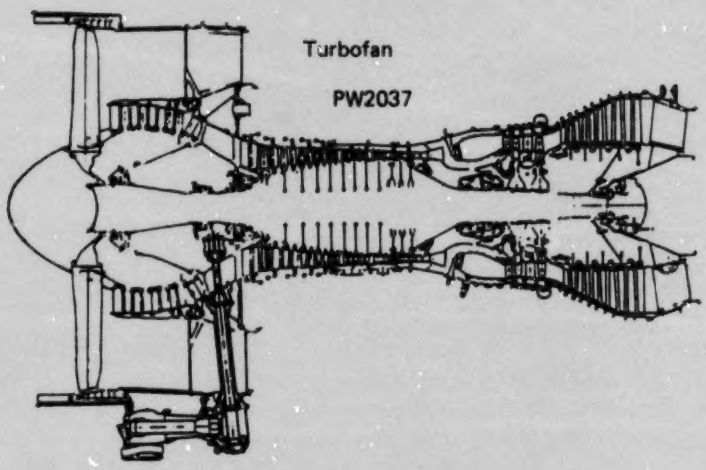
Trends, actual and projected, in the use of materials for commercial engines are shown in Figure 4-1. Related military applications are projected to follow similar paths. The new actor will be composites.

The panel examined a wide range of materials important to all aspects of aircraft development, airframe structures, propulsion systems and for other important aircraft subsystems. These are addressed in the body of the report in terms of the current state of the art, opportunities for improvement, and barriers to achievement of projected benefits. This is followed by projections of the progress of technology that could be realized by the year 2000 with the application of appropriate resources. Further information on materials as related to airframe structures is given in the report of the Panel on Structures (pp. 75-79).

Materials for Structural Members

Today, cast wrought and heat treated aluminum alloys are used widely as aircraft structural members and skins. Aluminum alloys also are employed in engine structures, fans, and compressors. Currently, the development of aluminum alloys with unique properties aimed at increasing overall cost-effectiveness is receiving and is expected to receive more attention. Two main thrusts are being pursued: ingot

State of the Art



	Material Use, % of Total Weight	
	State of the Art	Year 2000
Aluminum	8.5	20
Titanium	22.4	15
Steel	28.3	21
Nickel	38.0	20
Cobalt	0.5	–
Ordered alloys (Ti, Fe, Ni)	–	2
Composites/ composite reinforcement	2.2	21
Ceramics	0.1	1
TOTAL	100%	100%

Year 2000

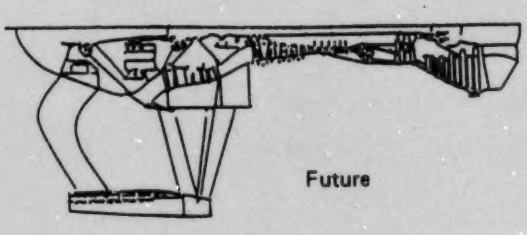


Figure 4-1 Propulsion system materials.

alloys and powder alloys. Ingot alloys in the form of aluminum-lithium alloys are for low- density structures, and the powder activity is directed at rapid solidification and mechanical alloying for complex forms with high integrity.

The aluminum-lithium technology is aimed at the production of low-density (6 to 12 percent) aluminum alloys with higher modulus levels, lower densities, and higher specific properties than are available currently. R&D activity is focused on combinations of aluminum, lithium, copper, and magnesium where damage tolerance, high-strength, and low-density characteristics are important. The goals of toughness and ductility and casting technology are still being pursued. It is projected that these problems will be resolved in the near future. It is anticipated that these materials will be available commercially in the late 1980s for use first in sheet and plate forms and later in forging and extrusion products.

The development of aluminum powder technology is aimed basically at producing more cost-effective aluminum materials than are currently available. The powder processing techniques being evaluated, as noted, include rapid solidification and mechanical alloying. Applications could include both aircraft structures as well as low-temperature engine components.

In general, powder systems offer wide chemical composition options with a range of improved properties. By the year 2000, these systems offer the possibility of improved strength-toughness-corrosion resistance with some 20 to 40 percent better performance than is now available from standard ingot products. Work on non-heat-treatable powder alloys has resulted in elevated temperature properties that challenge today's more costly materials such as titanium. The resultant alloys are capable of operating at some 550°F to 650°F with the potential for operation up to 800°F.

The production of low-density products is approached through the combination of such alloying elements as lithium, magnesium, and beryllium. These materials are in a more embryonic state than the others, but have the potential of further property improvements in the 2000 time period. The technology effort that could bring aluminum powder metallurgy technology to the application stage should include super plastic forming and squeeze casting techniques with particular attention to non-heat-treatable alloy technology leading to better high-temperature properties (800°F to 900°F); fundamental work on systems for low-density products; and modeling of the composition/microstructure/fabrication processes for tailored materials for specific needs.

Resin Matrix Composites

The use of reinforced plastics for aircraft structures has developed steadily over the past 20 years. Today, high-performance resin matrix composites are composed generally of high- and low-modulus graphite fiber reinforced plastics, and aramid fiber (Kevlar) reinforced plastics. Boron filament, carbon fibers, aramids, and glass filament provide significant weight saving for a given strength over the commonly used alloys, including aluminum, steel, and titanium. The high-modulus graphites, boron, and aramid fibers offer significant stiffening potential on a per pound basis for weight critical applications in the aerospace industry. Currently, these fibers are used as reinforcements. At present, military and civil aircraft, respectively, have fiber applications of about 10 percent by weight in current military airframes (F-16, F-18, A-7) and about 1 percent by weight in current civilian airframes (747, 727, DC-9). However, about 15 to 20 percent by weight of civil airframes are composed of other composites and plastic materials. The trend in usage of advanced composites is on the upswing. About 25 percent of the weight of the AV-8B airframe will consist of advanced composite materials. An advanced fighter being designed for use in the 1990 time frame will consist of approximately 50 percent advanced composites by weight. By the year 2000, the materials applied to aircraft should consist largely of graphite-epoxy composites, metal matrix composites, titanium, high-strength steels, and aluminum.

The next 16 years of development effort in advanced composites will be focused on enhancing toughness and tensile and compressive properties. To achieve these improvements, a number of problems need to be overcome. Chief among these is the development of a carbon fiber possessing a strain to failure of 2 percent or more, as well as higher stiffness fibers having good strain capability (i.e., greater than 1 percent). Also needed is the development of improved fiber compressive properties, better resin systems, low-cost processing schemes, surface treatments, and new molding compounds.

With domestic demand growing (annual rate of 71 percent from 1970 to 1980) and projected to grow in the period of interest, prices for carbon fibers have shown a dramatic decrease, falling from about $250/lb in 1970 to approximately $28/lb in 1980. Hence, enhanced material characteristics and lower price will tend to accelerate the use of this material if costs of production, test, and application can be constrained or reduced.

Advanced composites, particularly those that utilize carbon fiber reinforcement, could replace aluminum in the primary structure of aircraft by the year 2000. The relative advantages of carbon fiber composites are as follows:

- Their cost has declined dramatically and is attractive in contrast to other reinforcing agents, such as boron and aluminum fiber.

- o They have been "out of the laboratory" for more than 20 years.
- o Their specific strength and moduli are almost an order of magnitude greater than that of aluminum.
- o They offer minimized crack propagation, design flexibility, good compressive properties, and less material waste in production.
- o With the successful development of high-temperature resins, the combination of resins with carbon fibers will offer competition to titanium.
- o A high toughness composite could be attained with three dimensionally reinforced composites, by stitching or weaving.

Metal Matrix Composites

Metal matrix composites and laminates offer many new classes of materials with increased structural and environmental performance. Metal matrix composites (MMC) consist of reinforcement fibers or ribbons coupled with a metal matrix. The reinforcement is typically a strong, stiff material with little or no ductility, while the metal matrix has significantly lower strength but much higher ductility. Laminates consist of a sandwich structure with alternating layers of metal foil and fibers bonded together with an adhesive. In general, these composites combine dissimilar materials into a product having unique properties and are a blend of the materials that make up the composite. As a result, properties can be tailored by selection of component materials, and quite often cannot be obtained by traditional methods.

The tailoring of metal matrix composites can provide characteristics such as stiffness, strength, fatigue resistance, higher temperature, wear resistance, controlled coefficient of thermal expansion (CTE), low density, and improved damping that are superior to conventional materials. The composites can be applied throughout airframe and propulsion systems where cold and intermediate temperatures are experienced. Metal matrix composites are classified as continuous or discontinuous depending on whether the reinforcing fibers or ribbons are continuous or whether they are short fibers, whiskers, platelets, or particulates imbedded in laminating material.

Continuous metal matrix composites are typically in sheet form containing unidirectional fibers. These sheets can be laid up in different orientations and bonded to form thicker sheets with more uniform two-directional properties. Work for the past 15 years has placed major emphasis upon boron/aluminum (B/Al) and graphite/aluminum (G/Al) metallic composites with some work on such systems as

reinforced magnesium, titanium, and lead. This work has led to very small scale "commercial" activity. The current state of the art of unidirectionally continuous fiber, structural-type MMC can provide composites to meet new performance specifications. (B/Al composite support starts are being used in the space shuttle and G/Al systems are being used or considered for use in other space structures.) Typically the B/AI and G/Al have high strength, high modulus, and low density, although these properties are generally highly directional. Continuous SiC fiber metal matrix appears to be promising in terms of properties and low cost. More information on this material is given on pp. 112-113.. Major problems still must be resolved before these MMC systems can find widespread use in aircraft. These include:

- high material costs--both fibers and products. Composite prices range from $250/lb to $4,500/lb, with fiber costs being a significant portion of this amount. With the exception of some pitch graphite materials, most fibers for aircraft applications have increased in cost; however, the price of SiC metal matrix composite has been going down in the last two years;

- high material production costs--manufacture of these composites involves either liquid infiltration (graphite systems), diffusion bonding under vacuum (boron systems), or combinations that make the products expensive;

- deformation limitations--continuous MMC products can be joined with other materials by diffusion bonding techniques, but then further deformation is limited. This restricts secondary working, forging, rolling and extrusion;

- lack of techniques for machining and joining--such secondary operations require development. In addition, nondestructive and invasive inspection procedures need to be developed to provide high confidence in the integrity of parts and components;

- bond integrity--the bond between the matrix and the reinforcement phase in continuous MMC products is of primary importance. More fundamental studies are needed on interfacial bond systems (e.g., Navy Research Laboratory work on ion implantation coatings for various fibers), and additional effort is required to control and develop more effective materials;

- fiber improvements--greater ductility would be of great value, as would improved reinforcement materials. In particular, work on amorphous metal ribbons is needed; and

- high-temperature matrix material--most MMC products have used aluminum as the matrix material. Many advanced aircraft systems will require a higher temperature capability than is available with this product.

Current research and development efforts tend to be directed at parts production rather than at technology expansion. A coordinated, well-supported effort could yield the technology that would allow a significant improvement in effectiveness and costs by the year 2000. Possible advances could include a higher temperature capability (to 1000°F), better fabrication techniques to produce high quality, less expensive parts, improved ability to tailor properties, and better quality assurance procedures.

Additional effort could provide the technology for alternate matrix alloys (titanium, superalloys, unique aluminum alloys), hybrid structures combining these variations, and utilization of new unique fibers that could allow designs with further improvements in properties beyond the year 2000.

Discontinuous MMC incorporates staple, short fibers, whiskers, platelets, or particulates in a metal matrix (generally aluminum). Such incorporation can be done in a liquid state, but the current procedure uses a powder matrix. This system has several advantages over other composite systems. This reinforcement material is less expensive than the continuous fibers and can be produced on normal metal working equipment. These products tend to have isotropic properties (although somewhat lower than the unidirectional materials).

Significant work in this area has been conducted on silicon/carbide discontinuous reinforcement in aluminum/magnesium alloys. It appears that combinations of high strength (greater than 100 psi) and high modulus of elasticity (greater than 16 Mpsi) with reasonable levels of ductility (3 to 7 percent) can be achieved. Further, it should be possible, through the use of higher percentages of or alternate reinforcement materials, to produce very strong, stiff composites.

These materials are still in the early stages of development; however, with appropriate R&D effort they could be available in product forms by the year 2000. Areas of particular R&D interest include

- o models that can predict accurately composite properties from the properties of the individual components;
- o interface bonding parameters and optimum material combinations and consolidation procedures;
- o new aluminum powder alloys having properties now unobtainable from aluminum products, and expansion of the technology to other powder matrix alloys such as superalloys and titanium;
- o inspection procedures to define the quality of parts produced by these techniques;

- capability to produce large billets up to 10,000 pounds;
- improved fracture mechanics (ductility, toughness, and notch fatigue) and fabrication techniques; and
- reduction of costs.

Laminate structures generally consist of metal foil (mostly aluminum) with alternating layers of fibers bonded together with an adhesive in a sandwich structure. The advantages of this material relate to the sheet structures with higher specific strengths, improved fatigue resistance, and lower density. It is projected that laminates can provide a weight structure 20 to 30 percent lower than that obtainable with current aluminum sheet.

Work on these systems is in the embryonic stage. The potential is largely untapped. Thus, fundamental research can result in major dividends. Representative high-payoff technology developments would include

- high-temperature adhesives for high-temperature applications;
- fibers with ductility levels that would allow sandwich structure fabrication by sheet forming operations; and
- development of more optimum material combinations including foil produced from the new aluminum powdered metallurgy alloys or discontinuous MMC systems coupled with upgraded fibers for improved properties.

Currently, standard aluminum alloys coupled with Kevlar fibers are being developed. This effort could yield commercial sheet capability in five to seven years. Technology expansion in fiber development and optimum material combinations could further increase the weight savings over current aluminum sheet structures by 20 to 30 percent and possibly as much as 50 percent by the year 2000.

Further information on matrix materials for aircraft structures is given on pp. 115-117.

Hot Structures

Hypersonic aircraft will require structures capable of withstanding high loads at temperatures in excess of 1800°F. Severe temperature gradients also will be experienced. Candidate materials include available superalloys, some with thermally insulating surfaces and/or fiber reinforcement.

Recent developments suggest glass (and glass-ceramic) fiber composites as high strength/density--high toughness substitutes for superalloys. Toughness values in the range of many metals are possible and have been obtained. A current problem is the low softening temperatures of the glass matrices, but use of more refractory glasses or recrystallized glass (glass-ceramics) should make it possible to allow operating temperatures as high as 2200°F by the year 2000. An additional advantage of glass fiber composites is the possibility of achieving near zero thermal expansion coefficients for the matrix material.

Insulation offers another means for overcoming the temperature problems of high-performance aircraft. Table 4-1 outlines current activity as well as future work and benefits of improved insulation. It is reasonably certain that surface temperatures approaching 2700°F could be accommodated by the year 2000 through use of improved insulation.

Materials for Propulsion Systems

Significant improvements in gas turbine engine performance can be achieved by the year 2000 with aggressive technology development of high strength/temperature tolerant materials. These improvements will permit engines to operate at higher rotor speeds, temperatures, and operating pressure ratios, all important to improved propulsion efficiency. System studies show a 15 to 20 percent reduction in fuel consumption and a 15 percent reduction in weight and cost for a commercial turbofan and a 25 to 30 percent reduction in weight and cost for a commercial turboprop engine. For military fighter aircraft, a 50 percent improvement in thrust per unit weight along with a 25 percent reduction in cost are indicated possibilities. The benefits cited could be conservative; they could become greater as engine designers make more use of materials having higher strength-to-density ratios than materials of today.

Figure 4-1 is an overview of material utilization trends between now and the year 2000. The PW2037 engine was certified in December 1983. It will power the commercial 757 and the military C17 transports. The year 2000 engine presents data from a study conducted by Pratt & Whitney for NASA. Engine performance and weight improvements are expected to result mostly, but not fully, from increase in use of aluminum alloys; reduction in use of steel/titanium and steel/nickel alloys; introduction of ordered alloys of the types Ti_3Al, TiAl, Fe_3Al, and Ni_3Al; increase in composite and composite-reinforced structures; use of structural ceramics and ceramic composites; and use of ceramic thermal barrier coatings on turbine airfoils.

TABLE 4-1 Surface Insulation Technology Development

Technology	Benefits		Comment
	Year 2000	Year 2020	
Status			
o Low-density, sintered and bonded fibers o Silica o Reaction cured glass coatings	o Lightweight, closed cell ceramic foam o Long-life waterproof coatings o Flexible blankets for temperatures up to 2000°F		
Barriers			
Now:			
o Brittle o Low strength-impact resistance o Bonding systems o Coating stability at temperatures greater than 2700°F	o Efficient thermal protection systems o Flexible ceramic blankets o Durable coatings o Erosion resistance o Low surface catalysis at speeds greater than M 8		
Future:			
o Stronger, more refractory fibers o High-strength porous o Sol-gel technology		o High operating speeds and maneuvering flexibility	o Need M 20, high enthalpy test ceramics facility

Nickel and cobalt-base superalloys currently are used in the hot section of the engine (combustor and turbines). It is projected that by the year 2000 the static parts, such as combustor panels and turbine vanes, will use ceramic materials, but the rotating parts will remain metallic.

A major improvement in the capability of turbine airfoils is projected through the use of ceramic thermal barrier coatings on advanced superalloy systems. Increased component temperatures of 400°F to 600°F or a minimum 50 percent increase in strength can be expected.

Thermal barrier coatings are ceramic materials that are sprayed onto the surface of a turbine airfoil to insulate the underlying metal from the hot gas stream. A 300°F reduction in metal temperature can be provided by a coating applied with a thickness of 0.010 to 0.015 inch. These materials currently are applied to combustor and turbine vane platforms for improved durability.

The thermal barrier benefits would be enhanced appreciably if coating materials and processing methods were developed that extend coating durability to match the life of the component. This would include the ability to optimize coating, heat transfer, and adhesion.

There are a variety of advanced metallic alloys that can provide a 100°F to 300°F increase in metal temperature capability. These systems include advanced single crystal alloys, fiber reinforced superalloys, and oxide-dispersion-strengthened superalloys. These systems, presently under active development, could be made cost-effective and ready for application. It can be expected that with superalloys and coatings, a 53 percent increase in strength and 400°F to 600°F increase in operating temperature could be realized by the year 2000.

High-Temperature Structural Ceramics

In a recent study by the Department of Energy Council on Materials Science, it was concluded that a major problem with high-performance ceramics is the inability to manufacture them with reproducible characteristics. This is especially true for high-temperature load bearing applications. Another problem relates to flaws caused by damage during service (due to lack of toughness) that can lead to reductions in strength and catastrophic failure.

Nearly all toughening mechanisms identified thus far involve either composite materials or precipitation of a second phase in a homogeneous matrix. Several such mechanisms are possible.

- o microcracking: a large number of small cracks propagate. The increased fracture (surface) energy tends to limit crack propagation. This form of cracking generally results from a thermal expansion mismatch or a phase transformation in the disperse phase;

- o phase transformation toughening: Fife particles (the stable phase at low temperatures is of a lower density than the high-temperature phase) are prevented from transforming by the confining effects of the matrix. When a crack tip approaches a particle, the tensile stress allows the transformation to occur. This causes partial relaxation of the matrix stress, using energy that would otherwise propagate the crack;

- o prestressing: a differential thermal expansion between a fiber (or precipitate) and the continuous matrix places the matrix into compression; and

- o crack impediment: if fibers are of a much higher strength than the matrix, a crack will not propagate through the fiber but will bow out between fibers, thus creating more fracture surface absorbing more energy.

A few candidate ceramic materials for high-temperature load bearing applications purposely are not toughened (SiC, Si_3N_4). However, over the next several years most major advances almost certainly will involve toughening by one or more of the mechanisms described above.

In general, high-performance monolithic ceramics including Al_2O_3, mullite, MgO, and to a lesser extent ZrO_2, SiC, and Si_3N_4 can be considered as state-of-the-art high-temperature structural ceramics. With the exception of Si_3N_4, all find commercial refractory insulation applications where temperatures may exceed 3000°F, and also applications in severe chemical and rapid temperature excursion environments. In such applications, ceramics do not require high mechanical strength or toughness.

While alumina ceramics have dominated this class of materials, it is unlikely that pure Al_2O_3 will find application in load-bearing structures because of its lack of toughness and thermal shock resistance. Improvements have been realized by incorporation of a second phase to produce microcracking, or in the case of ZrO_2, a combination of microcracking and phase transformation toughening. Even in toughened materials, K_{IC} values do not exceed 5 to 7 $MN/m^{3/2}$, and fracture energies do not exceed 100 J/m^2.

Magnesium alumino silicate (cordierite) glass-ceramics with exceptional thermal shock resistance have been used as catalyst supports and heat exchangers at temperatures near 1400°C. However,

for applications in which high strength and toughness are required, these materials are inadequate.

Recent interest has focused on SiC, Si_3N_4, ZrO_2 and partially stabilized ZrO_2 (PSZ) (Y_2O_3-ZrO_2 and CaO-ZrO_2). Both SiC and Si_3N_4 maintain their mechanical strengths well above 1000°C. SiC, for instance, has been reported to have strengths that are maintained up to 1400°C, in the range of 400 to 500 MPa. A recent report from Japan indicates that strengths of a proprietary SiC material can approach 1000 MPa at 1600°C, but toughness values were not reported.

For Si_3N_4 reported strengths range from 300 to 500 MPa for reaction bonded material at 1200°C, to as high as 1,000 MPa for hot pressed samples in which the residual glassy phase at the grain boundary was fully crystallized. Toughness values in the range of 10 $MN/m^{3/2}$ have been reported for high-quality Si_3N_4.

Polycrystalline ZrO_2 and PSZ have received considerable attention due to possibilities of obtaining relatively high fracture toughness values from "transformation toughening." Strengths as high as 400 to 600 MPa have been observed for the PSZ system, but the destabilization of the surface via reaction with moisture tends to cause strength degradation at temperatures as low as 200°C to 500°C. Furthermore, the transformation temperature in the PSZ system is on the order of 1100°C to 1200°C, which precludes transformation toughening above these temperatures.

The values for strength and toughness reported above are generally for laboratory samples. The ability to fabricate large shapes with these characteristics is not in hand. Work in this field could be enhanced considerably by the establishment of a dedicated ceramics laboratory.

Glass matrix composites are materials in which the glass forms the continuous matrix and is reinforced by fibers of high strength-high modulus. Such materials offer considerable potential as structural materials in the temperature range of 600°C. There is reason to believe that this can be extended to about 1000°C by using a refractory glass matrix material.

Glass-graphite and glass SiC composites have been investigated with indications that room temperature strengths as high as 800 to 1000 MPa can be obtained. For a SiC-96% SiO_2 composite, short-term loads of 600 to 700 MPa can be withstood at temperatures near 1000°C.

Glass-ceramic combinations can avoid the difficulties associated with the higher processing temperatures of refractory glasses. Brennan and Prewo were able to obtain strengths of 800 MPa with K_{IC} of 17 to 25 $MPa/m^{1/2}$ at 800°C to 1000°C for an SiC reinforced lithium aluminosilicate glass ceramic matrix.

Fracture toughness values for ceramic material are among the highest observed and are close to being adequate for most applications. The major problem is the relatively low usable upper temperature.

Ordered alloys of current interest are titanium-, iron-, and nickel-base alloys (Ti, Fe, Ni) containing aluminum in which the amount of aluminum and other metal (M) are in fixed atomic ratios (MAl or M_3Al). These aluminides and intermetallic compounds, presently in development, can provide reduced weight, higher strength, and higher temperature capability. Titanium aluminides can extend the use of titanium to high-pressure compressor and low-pressure turbine airfoils and disk sideplates. Iron aluminides can be used for engine cases and seals. Nickel aluminides of the Ni_3Al type may improve the fatigue strength of turbine disks due to a more homogeneous deformation behavior. N/Al may have vane/blade potential. However, materials and process development including powder processing and casting are required.

Little work on ordered alloys with aluminum has been supported in the United States, and, considering the potential in this area, a major effort should be considered including the possibility of developing a pilot-scale manufacturing capability.

Carbon/carbon composites are unique "tough" ceramic materials for hot applications (up to 1500°F) in which strength and ablative resistance are critical. State-of-the-art carbon/carbons are being used presently for such things as the leading edges and the nose cap of the space shuttle, for rocket nozzles, and for nose tips on missiles.

Technical barriers to more general application of carbon/carbon composites center on relatively poor oxidative resistance at temperatures exceeding 500°C, their cost and reproducibility due to lack of understanding of fiber/matrix interactions, matrix composition effects, and the influence of fiber texture and morphology. Thus, present R&D effort centers on reducing processing costs, increasing life and operating temperatures, and improving oxidation resistance.

If successful, this effort should make it possible to increase the operating temperatures of carbon/carbon composite materials to about 1650°C. Another future benefit from the R&D effort would be the possibility of using carbon/carbon composites in place of superalloy components in engines. This could provide higher operating temperatures and a weight reduction of approximately 75 percent per component.

By the year 2000, it is envisioned that composites with a 100- to 200-hour service life at operating temperatures of 1650°C will be available, that precise design capability and the science of processing will be at hand, and that low-cost, short, automated processing schemes will be developed.

Initiation of work on "self-healing" oxidative protective coatings should result in materials with life of 300+ hours at high operating temperatures.

Facilities needed to realize these goals include the construction of stoichiometric combustion testing rigs as well as the construction of a pilot automated carbon/carbon production line to explore ways to reduce processing time and cost.

Resin Matrix Composite Technology--Polymers for Aeronautics

Ongoing resin matrix technology development is focused on processing procedures, elevated temperature performance and reliability, toughness, and fire resistance. Progress is being made. However, certain areas could benefit from additional effort and resources. An appropriately supported effort during the next 15 to 20 years should provide a scientific understanding of the chemistry and physics of the curing, processing, and performance of these matrix materials.

The anticipated work would include use of the computer in creating polymeric materials design methodologies to meet performance specifications. As more is learned about the prediction of mechanical properties from the basic molecular structure, the value of the computer as a tool will increase. Some of these improvements are discussed here.

Related bonded structures already play an important role in aircraft structures, and their use will increase in the years to come. Because of the similarity of the two technologies, similar matrix (resin) problems, to a degree, apply to both.

A recent study of matrices for the repair of composite structures by the National Materials Advisory Board of the National Research Council pointed out some research areas for review. The study considered ambient temperature matrix materials for adhesives or composites, and mechanical performance up to about 116°C. If the identified R&D work were supported, greatly improved resin matrix materials and processing capability would be available. Near-term work would include studies of the methacrylic acid derivatives of these materials. Longer-range efforts would involve studies on smectic monomers, reactive solvents, wave guide curing, secondary ring closure reactions, and donor-acceptor complexes.

The best materials available to improve the elevated temperature performance of composite matrices are the "350°F performance" resins. This is somewhat of a misnomer since these resin systems are highly susceptible to moisture and thus to performance degradation. Exposure of composites with these formulations to high humidity reduces their usable temperature to not more than 235°F. Important classes of materials being researched include NASA-Lewis-developed PMR (Polymerization of Monomeric Reactants) polyimides; bismaleimides; a variety of resins containing terminal and chain pendant acetylene groups; modified phenolic resins and a number of rigid chain heterocyclic polymers, the most common being polybenzimidazoles; polybenzothiazoles; polyphenylquinoxalines; polyquinoxalines; and polybenzoxazoles.

A major development obstacle is the difficulty of processing. Most molecules based on these rigid backbone systems have high softening temperatures. This characteristic makes them good high-temperature performers, but intractable and difficult to process under desirable conditions (200°F to 260°F). By the year 2000, improved elevated-temperature performance composites will be available. However, the magnitude of these improvements are not predictable at present.

The on-line processing reliability of composite structures (a chemical process) should have a sound scientific base by the year 2000. Research over the past 10 years has established the necessary chemical and physical analytical technology to assure high-quality starting materials (prepregs). Rudimentary models are already at hand that deal with material compaction, chemical reaction kinetics, matrix rheological change, void formation and suppression, and tool and hardware heat transfer dynamics. Through current efforts, mathematical models are evolving that will assist in material and process selection. It is predicted that within about 5 years it will be possible to obtain signals (dielectric and acoustic) from hardware curing in a press or autoclave, which will define the chemical and physical state of the material being processed. These signals would be used to provide product consistency through use of computer process control.

Current and past research on fire resistance has yielded materials that can do a respectable job for aircraft interiors, although recent events dictate need for further improvement. Aircraft exteriors are another story. Composite materials will play an increasingly important role in primary aircraft structures. By the year 2000, these materials could well be the major component of the aircraft structures. Research and technology development activities are required that will lead to composite matrix resins with fire retardency, low smoke content, and low combustion gas toxicity. With composites destined to become a major aeronautical construction material, resistance to day-to-day handling also becomes a major

concern. Tougher matrix resins are needed. A current approach to toughness is the incorporation of microscopic dispersions of elastometric polymers as a discrete phase in a more brittle continuous matrix resin. This improves toughness; however, elevated temperature performance is reduced. A less explored approach is alloy polymers or interpenetrating polymer networks (IPN). IPN results from two different cross-linked polymer networks, synthesized sequentially or simultaneously within each other. By the year 2000 this research should provide polymers for aeronautical applications that have the operational characteristics and performance economies that will allow their broad use.

"Thermoplastic" approaches are a special case of toughened matrix materials. The structural performance of thermoplastics, such as the polysulfones, are of definite interest. Composite fabrication is cost-effective. However, poor solvent resistance can be a problem in aircraft construction. (For space application the future is bright.) However, more theoretical work remains to be done before the thermoplastics are thoroughly understood and their viability assured. Increased research is recommended. Most recently, experimentation with a polymer called PEEK (polyetherether ketone) demonstrated the superiority of this material over other thermoplastics. Composites based on this matrix display a high degree of toughness, stiffness, and much greater solvent resistance. Dynamic mechanical measurements show that, because this polymer has a considerable degree of crystallinity, the modulus falls only slightly above the glass transition temperature. Current thinking is that thermoplastics with crystalline domains and the capability of cross-linking in the amorphous regions will have much future value.

Considerable effort will be required to design the proper crystalline domains in both chemical structure and percentage of the total polymer matrix. The polymer morphology of the matrix in the presence of the composite forming fibers also must be studied, controlled, and understood. Techniques for crosslinking in the amorphous domains must be developed. Finally, the high processing temperatures must be dealt with since they are both a physical and psychological deterrent. PEEK, for instance, requires processing at 400°C.

There are other polymer concepts that should prove of value to the aeronautical industry by the year 2000. Two outstanding candidates are the molecular composites stemming from research in the rodlike polymer field and electroconductive polymers which should have future electrical and electronic applications.

Molecular Composites

Recent progress in the synthesis of mesomorphic rigid rod polymers has led to the concept of molecular composites that consist, in part,

of conventional flexible coil polymers. Avoided are impediments such as interfacial adhesion and different thermal expansion coefficients. Above a critical concentration, the rigid rod polymer segregates into crystalline domains, dispersed in the flexible coil matrix. The concept also overcomes many processing difficulties associated with rigid rod polymers caused by high or no melting points and limited solubility. The net result is a moldable, lightweight, dimensionally stable material with tunable properties that is chemically and thermally stable and possesses fracture and impact toughness.

For example, poly PPBT (p-phenylenebenzothiazole) is an intrinsically rigid rod polymer that assumes the straight rod conformation even in dilute solution. Flexible coil host polymers are an amorphorus nylon 6,6 (Zytel 330) and poly ABPBI (2, 5 (6) benzimidazole). PPBT and ABPBI are typical high-temperature-resistant aromatic heterocyclic polymers and exhibit neither a melt nor glass transition temperature. Both fiber and film molecular composite properties were achieved by solution processing.

In these cases, composite properties are substantially superior to the host polymer in tensile strength and modulus (Table 4-2). The molecular composites have specific mechanical properties better than steel and are comparable to high-tensile-strength graphite fiber/epoxy composites. Much work remains to better understand the processing, property, and structure interrelationships. Because advances in material manipulation offer the possibility of significant improvements, an effort to develop an understanding of and capability to use such materials demands significant attention, on a par with the alloying of metals effort.

Titanium/Engines

Fan blades currently are forged from titanium alloy Ti-6Al-4V. For improved fan performance, it is desirable to have fans operate at higher speeds without the use of blade bumpers for damping. To achieve this objective, fan blades in the year 2000 could be made of higher strength and stiffness materials and will be hollow for reduced weight. Titanium composites with improved ductility will be required for fabricated blades. An alternate, reduced-cost approach would be cast high-strength alloy hollow blades. The casting technology will require development of the appropriate mold and core materials to minimize reactivity and thereby provide cast-to-size parts.

Shafts, Bearings, Gears

Various steels are used for shafts, bearings and gears. In order to attain the higher rotor speeds for the year 2000 engines, steels with improved strength and fracture toughness will be required for

TABLE 4-2 Molecular Composite Properties

Material	Modulus of Elasticity, Mpsi (GPa)	Tensile Strength, psi (MPa)
Nylon	400,000 (2.75)	14,100 (97.3)
60/40 PPBT/Nylon	11,725,000 (80.9)	120,000 (82.7)
ABPBI	5,280,000 (36.4)	158,000 (1090)
60/40 PPBT/ABPBI	32,300,000 (223)	210,000 (1490)

bearings and gears. Gearbox durability is considered to be one of the life-limiting features of advanced turboprop engines. At higher rotor speeds, shafts of greater strength and stiffness will be required. Improved bearing and gear materials require special attention to the surface properties of the finished component. Good properties can be achieved through use of ultraclean melt stock and through controlled surface processing using electron beams or lasers. The improved stiffness and strength of shafts can be achieved through composite reinforcement. Process development is required in all areas.

Fuels and Lubricants

It is generally agreed by knowledgeable sources that the major fuel problem of the aviation industry is one of maintaining current quality standards as oil supplies dwindle. Although as this report is written there is a worldwide oil glut, it seems prudent for the United States to continue a reasonable level of research and development effort on aircraft fuel and engine compatibility. This issue has been the subject of two relatively recent studies by the National Research Council under the sponsorship of NASA and the U.S. Air Force (see bibliography).

Future fuels for airbreathing aircraft engines will emphasize energy density and will require improved thermal stability since they are likely to be used as a heat sink in future advanced high-speed aircraft.

The development of aircraft lubricants will focus on improvements in oxidative and thermal stability, reduced volatility, and lower pour points, since it is predicted that future aircraft engines will operate at much higher speeds than current engines. At Mach 3, bulk oil temperatures of 260°C (500°F) could occur. Among the more interesting lubricant candidates being studied are the fluoroether

triazines which are reported to have an operating range from -30°C to 316°C. Other major advances in lubricants are likely to result from optimized design of tribological components and application of solid lubricants, mechanical devices, and inert atmosphere lubrication systems.

Materials for Subsystems

New types of materials to be introduced in the next 10 to 15 years are expected to be key to major advancements in aircraft sub-systems. The status of some of these materials and components such as fiber optics and power conductors, higher energy fuels and improved lubricants, fuel cells, and other electro-chemical power generating and storage systems, stronger but lighter landing gear assemblies, and lighter interior materials with greater fire resistance are discussed in the following sections.

Fiber Optic Sensors

The increased use of nonmetallic composite structures in aircraft has presented a problem--testing for structural integrity. Proof testing methods and analytical formalism have been developed for quality control of brittle materials. These techniques involve subjecting the device or component to applied loads much larger than expected service loads for short time periods (proof test). Measurements or estimates of material flaw size can be used to estimate expected structural life under given loadings.

These relatively crude techniques rely on the similarity of stress distribution between proof test and in-service conditions and do not take account of in-service damage, impacts, variations in stress, or surface abrasion. Therefore, the usual recourse to assure safety is to overdesign the structure.

Fiber optic and organic piezoelectric sensor developments offer the promise of better-quality measurements and safety assurance. Fiber optics sensors, glass or plastic fiber waveguides wound in small spools, detect very low amplitude acoustic signals. A variety of techniques are used to detect the passage of acoustic waves through the spool or structure in which the fibers are enclosed. These techniques, all optical, generally measure the resulting cyclic change in velocity of the optical signals in the fibers (interferometric method), or the change in propagation intensity in the fiber due to acoustic signal mode mixing. The Department of the Navy has developed the interferometric method for passive sonar devices. Similar principles can be adapted to the detection of acoustic emission from strained composite structures.

The organic piezoelectric sensors that work by electrical detection of acoustic signals can be designed into large arrays mounted on a flexible plastic sheet.

An acoustic sensor system could be designed as a network of acoustic detectors and built into an airplane's composite structure. The detector materials, thin glass fibers or thin plastic sheets, would be compatible with composite materials. They could be glued to the internal surfaces of the components as listening blankets, or incorporated directly into the composite. The devices, coupled to communication links, would transmit their signals to a master computer. Time delay spectroscopy can identify the source of the signals and acoustic emission analysis can determine the development of flaws. Since the sensor system is very light, it would add negligible weight.

These systems, coupled with a fundamental knowledge of failure processes, could provide real-time evaluation of structural integrity yielding early warnings of impending component failure. These systems, of course, could be used in components proof-testing prior to major system assembly. Fiber optics sensors have operating temperatures above 500°C and can be used for temperature sensing, or chemical sensing in constrained locations.

The basic technology for the design of such systems is essentially in hand. However, for aviation applications, integrated system R&T is necessary to integrate sensor development, acoustic emission analysis, computerized evaluation of brittle material integrity in actual structural work on composite component testing. More specifics on these sensors are presented in Table 4-3. This is an area where relatively small investments may have major, revolutionary effects on aircraft safety, failure avoidance, and maintenance costs. With proper support and direction, integrated computer/sensor systems designed to evaluate conditions in the aircraft structure (and propulsion systems) are possible in the 2000 period.

Fiber Optic Communications

Fiber optic communications systems are beginning to replace twisted pair and coaxial cable systems for ground-based telephone and data transmission. Fiber optics systems offer advantages in bandwidth (1,000 times higher than conventional) and in much smaller size. Aircraft uses of fiber optics communications are even more favorable due to lower cable weight, smaller size for cramped conduits, and insensitivity to the proximity of power cables. In addition, in future aircraft the replacement of metal structures by nonshielding composite structures makes the communications system more vulnerable to RF interference from power cables, lightening, and other electromagnetic noise. This interference would be avoided.

TABLE 4-3 Structural Test Sensors

	Fiber Optics	Piezoelectric
Current Status	Defense--high development for hydrophone, geophone applications No NDT applications studies Slow commercial development	Very slow Interest is mostly in miniature microphones and fiber optics coatings
Problems	System integration Failure detection protocol Time delayed spectroscopy for identification of failure source Computer interfacing and system design	Materials development Time delayed spectroscopy
Potential Benefits	Proof-testing of components In-flight quality assurance Early warning of structural component failure Identification of flaw location	In-flight testing of strain, flaw development Integral component of tested structure Could be applied as paint coating
Timing	5 years' testing and development 8-12 years' implementation in the field	15 years before aircraft test

Estimates of weight reductions of the communications system transmission lines by as much as 20,000 times are only the beginning of a long list of desirable features of optics. Presently the Department of Defense is outfitting several experimental airplanes (such as the AV-8B Harrier II) with fiber optics communications links.

There are problems, however, for the commercial adaptation of what appears to be a very promising system because of lack of attention. They include cost, component reliability, and system design. Manufacturers of glass fibers expect that cost will decrease with greater mass production, but it is not clear when this will occur. Active element reliability is still not good enough due to short source lifetimes. Today, the major roadblock is in system development and computer interfacing.

By the 2000 period, integrated communications systems with optical fiber waveguides are feasible for aircraft operations if R&D support is provided.

Electrical Power Conductors

In the Douglas MD-80, electrical wiring and switches account for approximately 1,830 pounds of the total aircraft weight. By replacing the copper wire on the aircraft with highly conductive, intercalated graphite fiber, it is estimated that a weight savings of approximately 75 percent could be realized. Significant research and development effort has been directed toward producing high-quality, conductivity intercalated graphite fiber. At present the levels of conductivity exhibited are approaching that of copper. The principal technical barrier to high-performance, viable systems is adequate connectors. Graphite fiber is highly anisotropic in character. The transverse conductivity is very poor relative to the longitudinal conductivity. The connector must contact all the basal plane edges and not just the outer fiber surface to achieve a constant current over a relatively short length of "cable." Another area for research relates to development of economical processes to intercalate continuous lengths of fiber. Intercalation will proceed rapidly where the edges of basal planes are exposed, but slowly where basal planes wrap around the surface of the fiber. Thus, texture variations in the fiber will significantly affect the degree of intercalation achieved and the uniformity of fiber conductivity. Finally, the stability of the intercalated fiber over various operating conditions and time is not known. Future research activities should be directed toward these technology issues.

It is projected that by the year 2000, stable intercalated fiber of long lengths will have been developed. This will be the result not only of newly developed intercalating agents, but also of the development of significantly improved, high-modulus graphic fibers and good connector devices.

In order to realize these developments, it will be necessary to increase research efforts. A dedicated fiber development laboratory would be of considerable assistance in this pursuit.

Electrical Power Storage

Emergency backup electrical power presently is obtained from lead-acid batteries. In aircraft systems, power-to-weight ratio and power density output are important concerns. While lead-acid and nickel-cadmium batteries have offered the best alternative to date, new materials are being developed for electrochemical power generation. These include high-temperature ceramic fuel cells, ceramic sodium-sulfur batteries, and newly developed conducting polymer batteries.

Ceramic sodium-sulfur batteries promise increased power-to-weight ratios over the common lead-acid batteries. Simply, a ceramic porous membrane (sodium beta-alumina) separates two electrolytes, one rich in sodium and one rich in sulfur. The porous membrane passes sodium ions with very high conductivity, but is impermeable to neutral sodium atoms. This allows a net flow of charge across the membrane with compensating electric magnetic force developed at the electrodes. The major problem in the development of the ceramic sodium-sulfur battery has been the ceramic membrane. Single crystal beta alumina exhibits a high enough conductivity to favor this process, but its excessive cost and lack of shear strength has prompted the study of other materials. Polycrystalline beta-aluminas with various dopants have been tested. But they have a lower conductivity. Grain boundary reactions give them a very low ability to sustain continued cyclic charging and discharging. Inorganic glasses that do not suffer from grain boundary effects have been tested with mixed results. Some exhibit high conductivity, but are highly reactive to aqueous corrosion.

Ceramic batteries are under development. It is difficult to predict whether sufficient control can be exercised over the membrane materials to make these batteries commercially competitive.

Conducting polymer batteries are a new concept. Some work has been expanded over the past 10 years at large laboratories such as Xerox, IBM, and Allied to develop conducting polymers. These materials are produced by doping normally insulating polymers such as polyacetylene with charged ions, such as iodine or arsenic pentaflouride, creating charged carriers (electrons or holes) in the polymer structure. Films made from these polymers are immersed in electrolyte solutions to develop the electric potential.

With a projected time of development of 5 to 15 years, the conducting polymer batteries offer power-to-weight ratios and power densities 10 times better than lead-acid batteries, and cell voltages

of 2 to 3.7 volts. Their energy density is projected to be equivalent to the lead-acid battery.

These new batteries and fuel cells, because of reduced weight and maintenance, could be distributed power sources located near the components that they power, reducing the need for large power bases.

The outlook for conducting polymer batteries appears better than for porous ceramic membrane batteries. There are problems with both. In polymer batteries, there are problems with atmospheric attack and instability of the doped polymers, but research into better dopants, better materials, and protective encapsulation are warranted and ongoing.

Future research involves the development of better conducting polymers and stable electrolyte systems for the polymer batteries, and fast ion conducting glasses to replace ceramics in the sodium-sulfur batteries. A large NASA effort in these areas may not be needed, since these devices are being developed for other than aircraft purposes.

Landing Gear

The landing gears for most aircraft are composed of two major assemblies: the main structure (strut and truck) and the rolling gear (tires, wheels, and brakes). The landing gear is one of the unique safe life components within the aircraft structure. Its weight on a large aircraft is significant, so that weight reduction is very important.

Because the landing gear is massive and highly loaded, it is one of the few areas where high-strength steel can be a weight-effective design material. As such, most gear struts and trucks have been designed predominately of high-strength 300M steel. Much effort has been directed to using the last drop of strength while avoiding stress-corrosion, hydrogen embrittlement, and fatigue failures. Manufacturing costs tend to be high because of the many stringent processing requirements.

The most efficient wheel material has been 2014 aluminum. This provides good elevated temperature operation but is susceptible to corrosion fatigue failures that lead to wheel surface cold working, anodizing, and painting for protection. The most recent material breakthrough has been the replacement of steel disc brakes with reinforced carbon, which reduces weight of that assembly by about 30 percent. Most tires have evolved from automobile and truck tire developments, but lags that industry by several years in the application of advances.

Although titanium can be weight-effective in some applications, fire safety discourages its use. However, some titanium is used in braces and links.

Advances to the year 2000 will depend upon a number of developments. Advances in high-strength, tough steels, is a challenge which, coupled with selected application of SiC/Al and SiC/Ti, could reduce strut and truck assemblies weight as much as 10 percent, improve corrosion resistance, and reduce manufacturing cost. Difficult development problems confront the tire manufacturing industry in their efforts to produce a longer-life, safe tire. It is anticipated that aircraft tires will continue to evolve from the technology advances in the auto industry. Powder metallurgy developments will be applied to a better wheel material providing longer life with fewer inspections. Most of the brake improvements will revolve around advanced carbon systems to increase reliability and life and to reduce manufacturing costs.

Interior Materials

During this past decade, interior material developments have been directed toward aircraft fire safety. In addition, recent effort has been directed toward weight reduction for new aircraft interior materials. For example, carbon phenolic and Kevlar phenolic faced honeycomb panels are replacing aluminum or glass faced panels as a weight-saving item. Tedlar faced aluminum is replacing ABS molded sidewalls as a safety improvement. Special fire-resistant fabrics are being used in seats to protect the urethane foam cushions from fire.

Still, the most significant deficiency with current interior materials relates to fire safety, greater fire resistance, and reduced toxic volatiles associated with combustion. New developments are expected to effect improved fire safety, but it is not anticipated that developments will impact weight.

Performance Assurance

Because of the chemical complexity of many new materials, processing is an important factor in determining final properties of these materials. This causes difficulties in monitoring the processes for control of the final products and their properties.

Consistency of raw materials, both in their physical (particle size, shape, etc.) and chemical (impurities, surface contamination, etc.) constitution, are of importance. Where fibers are a "raw material" for composites fabrication, additional characterization and control of physical properties will be important. Identification of

minor phases and surface constituents and characteristics are of equal importance.

In many instances the technology has not reached a point where consistent raw material characteristics can be achieved, but with few exceptions, the necessary characterization techniques are available. For example, tools for particle size and shape, from a few nanometers up, are commercially available; chemical and instrumental techniques for quantification of impurity levels are also generally available; and surface contamination often can be determined by modern surface analytical techniques such as Secondary Ion Mass Spectrometry, Auger Spectroscopy, and X-ray Photoelectron Spectroscopy. What is needed is careful integration of such techniques to provide material control followed by process controls to help assure consistent, qualified end-products.

The processing itself is, in general, under a high degree of control, but again because of the complex chemical changes that occur in processing, characterization of the product in terms of microstructure and final chemistry is not easy or consistent. In inorganic monoliths, identification and location of major and minor phases is necessary but often difficult. Grain boundary characterization is of extreme importance, since high-temperature mechanical properties of metals and ceramics may be controlled by the grain boundary but is again a difficult determination.

In composites the matrix-reinforcement interface presents several problems. Many of these problems cannot be properly characterized without testing under actual operational conditions. Interfacial bond strength, important in toughening and strengthening, is one such property.

The chemistry of the interface can be determined by a number of analytical techniques, particularly Auger spectroscopy. On the other hand, the identification in the structure of minor phases is difficult, and advanced X-ray techniques are required. Thus, it is clear that much work is needed to be able to assess the operational worthiness of final components.

For monolithic ceramics or any brittle matrix material employed in composites, it is imperative that nondestructive techniques be available for detecting small, strength-impairing flaws. Important defects may be on the order of 50 MM in size. This presents a major, as yet unresolved problem. The problem also applies to metals and especially to metal composites where it is necessary to assure proper material properties for safe operation.

As more complex structures evolve, it will become increasingly important to test continuously during service for flaw initiation and growth in critical structural elements of the aircraft.

Radiographic and ultrasonic techniques have been applied to all types of composites, but there is limited experience with ceramic composites. Experience gained on fiber reinforced plastics will no doubt be of value in high-temperature composites, but a considerable effort will be required before correlations between properties and the response of a material to various evaluation techniques can be made.

It is not yet clear how "real-time" evaluation can be accomplished, and major effort will be required if this is to become a reality.

Report of the Panel on

Guidance, Navigation, and Control

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GUIDANCE, NAVIGATION, AND CONTROL

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GUIDANCE, NAVIGATION, AND CONTROL

Introduction

Guidance, navigation, and control (GNC) systems have historically been vital to improving operational capability of aircraft. The development of autopilots and electronic navigation systems has greatly aided the crew in flying precise routes in all weather conditions while at the same time reducing pilot workload. Advances in high-integrity onboard computing and electronics technology have resulted in a significant increase in the capability of these subsystems to perform more reliably, efficiently, and safely.

Onboard computing and control system capability has provided new design approaches for the aircraft designer. By using automatic control systems to stabilize the aircraft, the designer can relax certain conventional aerodynamic stability requirements and achieve aircraft performance benefits. Thus, modern fighter aircraft are designed with low levels, or in fact, negative levels of longitudinal static stability to boost maneuvering capability and cruise performance, relying on the use of full-time, full-authority automatic stability augmentation systems to stabilize the aircraft.

During the next 20 years, GNC systems will become a driving force in aircraft design. Instead of making separately designed major aircraft systems work together, the designer will exploit the interaction and integration of aerodynamic, structural, and propulsion system controls to provide a better aircraft.

The benefits of such integrated designs have been demonstrated already. Integrated digital control of the engine inlet and autopilot systems on a NASA YF-12 research aircraft resulted in a range increase of 7 percent. A civil transport derivative using extensions on each wing and an active control system to minimize the requirement for structural modifications achieved significant cruise performance improvements.

These are first-generation applications of advanced GNC systems. More significant benefits are achievable by the year 2000. Complete integration of aerodynamic, propulsion and structural controls, and mission avionics will provide dramatically better aircraft performance, new capability (low observability, supermaneuverability) and/or improved mission effectiveness. This requires a concurrent, multidisciplinary design approach early in the design stage.

The role of advanced GNC systems in future aircraft is not an option. The select government-industry-university Aeronautical Policy Review Committee, in reviewing National Aeronautics Policy, stated in their November 9, 1983, report:

> Systems integration will play an increasingly important, if not dominant role in the development of advanced technology aircraft . . . advances in the traditional aeronautical disciplines will no longer ensure a superior product.

Hardware advances in the next two decades will provide greater computational capability, improved reliability, and reduced component cost. These advances, in the next decade or two, in themselves are not the pacing technology developments. Rather, the use of these advances in multidisciplinary design is the issue and research challenge of the 1980s and 1990s. Thus, the dominant GNC technology theme is one of generating the knowledge base necessary to take maximum advantage of GNC system capability in both civil and military aircraft design. The payoff is real, but the improvement of the state of the art and science in multidisciplinary design of highly interactive systems requires much attention.

The mission environment, civil and military, in the year 2000 poses a truly significant challenge for the technical community. For example, for the combat aerospace vehicle of 15 to 20 years hence, to be effective, it will have to deal with massive amounts of information such as: targets, ground and airborne threats, navigation data, route options, weather, weapons, aircraft system status, and commands. This information will have to be collected, stored, processed, correlated, integrated, analyzed, and acted upon in a very short period of time. Equivalent requirements will exist for civil operations. These mission requirements and the resulting technology developments in onboard data handling, computation, data integration, and application for improved mission effectiveness represent significant challenges to the technical community.

State of the Art

The state-of-the-art assessment here concentrates on the capability of the current technology to provide functions, systems, and applications, rather than on aircraft component technology. It is believed that the component technology will progress on its own merits and that the critical developments in technology will relate to integration of the advanced major aircraft systems and components to provide broad gains in performance for the complete, integrated systems aircraft.

Guidance and Navigation Systems

Functions Navigation/guidance functions and limitations are summarized in Table 5-1. Conventional civilian aircraft generally are well served by state-of-the-art navigation systems, as they are able to

TABLE 5-1 Guidance/Navigation Functional Capability

State of the Art	Limitations
3D enroute navigation using ground-based NAV AIDS and dedicated sensors for inertial aiding	Ground-based air traffic control (ATC) unable to fully exploit onboard capabilities to optimize airspace management
Optimal flight path management for commercial transport missions	
Radar beacon/voice for en route, terminal area ATC guidance	Manual interaction process
Automatic terminal area guidance supporting autoland instrument landing system (ILS)	Constrained approach flight path insufficient for STOL operations to damaged runways
Tactial guidance using ground and airborne navigational data	Limited ability to collect, organize, integrate and display large amount of data available
Terrain-based navigation	Operational effectiveness usually classified

navigate typically to fractions of a mile en route. Flight management systems provide trajectories that optimize the climb, enroute, and descent phases of flight for fuel efficiency. In the approach and landing phase, current systems have the capability to totally automate the operation. Current air traffic control (ATC) methodology, based on prescribed, finite sets of network elements (e.g., airways, intersections, and airports), constrains aircraft flight path options, and of necessity, creates high-density traffic in the selected corridors. As a result, the current ATC system cannot efficiently exploit existing onboard 4-D guidance and navigation capabilities. A major challenge will be to accommodate a mix of aircraft with or without 4-D capability that would allow all the aircraft to realize benefits of an advanced ATC system without penalty. Interaction of aircraft and ground facilities is currently through radar beacon and voice commun-

ications, limiting information content and transfer speed. This will need improvement.

In the military environment, peacetime missions are supported, adequately utilizing civil airspace facilities augmented by tactical air navigation (TACAN) and airborne/ship traffic control systems. Terrain-based navigation methods are utilized for specialized tactical and strategic missions by the military. The limitations of such systems relative to accuracy, operability, and observability generally are classified, but the high demands on such systems will warrant continued improvement.

Navigation and guidance (including the use of damaged airfields for military operations) in weather or at night, for conventional or short take off and landing (STOL) aircraft, are not accommodated by current terminal area equipment. Digital information data links between aircraft and the command/control/communication facilities are considered state of the art. These systems are limited in the areas of data collection, processing, integration, correlation, and display to the pilot. Memory limitations are also a barrier with regard to worldwide onboard terrain and facility data.

Subsystem Capability The accuracy and capability of state-of-the-art navigation elements are summarized in Table 5-2. These characteristics are achieved with commercially available equipment. Strapdown laser gyro inertial systems are state of the art in civil and military aircraft.

Navigation System Integration and Pilot Interface The state of the art for transport aircraft consists of integrated flight management systems for navigation and autopilot control. Such systems are also under development for fighter aircraft. The integration of the air data, inertial reference, and flight control systems has been evaluated analytically and experimentally, but has not been applied operationally.

Some consolidation of situational information is accomplished on both military and civil aircraft, as evidenced by combined navigation/threat displays, horizontal situation/weather radar displays, and combined trajectory guidance/vehicle-state information on head-up displays. However, the pilot remains the dominant situational information integrator in both civil and military missions.

Control Systems

A summary of impediments and limitations in control system technology is contained in Table 5-3.

TABLE 5-2 Navigation Subsystems Functional Capability

Type	Accuracy	Capability
Inertial	0.1 - 1.0 nm/hr	Electrostatic & laser gyros
Ground-based VHF NAV	0.2 - 2 nm	Location sensitive, limited geographical coverage
Omega with inertial smoothing	1 - 2 nm	Virtual worldwide coverage
Loran C	0.1 - 1 nm	Coverage/smoothing dependent
ILS/MLS	1 - 2 at touchdown	Terminal area coverage, MLS not generally available
Radio altimetry	Less than 1 at touchdown	Approach and landing coverage only
Barographic altimetry and airspeed	Alt - 50 ft at sea level 200 ft @ 35,000 ft Airspeed - 5 knots	Adequate for air route vertical separation
Navigation satellites	Civil use - 30	Limited use (eventually worldwide)

TABLE 5-3 Flight Control System Impediments and Limitations

Models for the aircraft, its systems environment, disturbance, and command characteristics for full-authority integrated active control design are inadequate or lack flight verification.
Experience, tools, and criteria for multidisciplinary design of integrated controls for highly interactive elements are lacking.
Excessive lags, limited field of view, and pilot behavioral differences affect the utility of ground simulation.
Only empirical methods are available for collection, integration, and display of multisource situational data, and pilot is required to accomplish most information integration.
Empirical knowledge as used is not adequate to explain interactions of human and complex GNC/display systems and their effects on human performance.
Systematic design and development methods for allocation of control requirements among control effectors for normal/failed conditions are lacking.
Only subjective criteria are available for verification and validation of complex digital systems.

Knowledge of impact of design decisions on ultimate system complexity, reliability, integrity, and development burden is lacking.

Functions The state of the art of control system functional capability is shown in Table 5-4. Flight control state of the art is perhaps best epitomized by the space shuttle digital fly-by-wire control system which provides control of the vehicle from on-orbit maneuvering, through atmospheric entry, from Mach 25 to a horizontal landing using blended reaction and aerodynamic controls. Full authority digital fly-by-wire flight control has been incorporated in operational military aircraft. Applications to civil aircraft, prompted by potential performance advantages in aerodynamics, structures, and operations have been initiated. Its delayed application in civil operations appears to be due to concerns over reliability, maintainability, and integrity of such systems and in the perceived need of such systems. As is evident from Table 5-4, an extremely large range of control functions has been demonstrated on aircraft or missiles.

Limited application of the more highly sophisticated active control functions has been due principally to the lack of confidence that predicted benefits actually can be achieved without undue risk or penalty. This is especially true for flight-critical structural mode control and for control of highly interactive aerodynamics, structures, and propulsion systems. The knowledge base required for full realization of these systems must contain both theoretical and real experience with such applications so that theory can be validated in such areas as pilot control and maneuvering requirements, atmospheric and electromagnetic effects, and aeroelasticity and unsteady aerodynamics interactions.

Computer-aided design tools, synthesis methods, and the design criteria for specifying these complex flight control systems are not mature and require further development.

Control Integration The traditional process of systems integration is to make individually designed subsystems work together on an aircraft, i.e., to ensure compatibility and minimize adverse interactions. The ultimate goal is to carry out concurrent multidisciplinary design of the highly interactive systems to maximize total aircraft performance. Here, deliberate consolidation and interaction of functions and subsystems is sought to achieve new capability or to exact higher performance than possible with independent, individual subsystem design. There are also intermediate levels of systems integration where, for example, selected functions or subsystems are linked to make use of selected data for improved performance. The coupling of the throttle, flight control, and navigation systems to provide automatic flight path control is one example of subsystem integration.

TABLE 5-4 Control System Functional Capability

Control Function	Operational		Development		Experimental
	Civil	Military	Civil	Military	
Digital fly-by-wire		FW	FW, RW	RW	FW, RW, Fly-by-light
Low bandwidth active controls					
Maneuver load control	FW	α, g limiters	Continuing		
Gust load alleviation	FW		Continuing		
Relaxed static stability	FW, RW	FW	FW	FW	FW - Highly unstable
High bandwidth active controls					
Ride control	FW-nuisance modes	FW - Low level mission			RW - Higher harmonic control
Flutter suppression					FW - Adaptive stores flutter suppression
Task tailored control modes				FW	
Self-adaptive control modes		Limited-FW			
Digital engine control	FW	FW	Continuing FW, RW	Continuing FW, RW	
Engine inlet controls		FW			
Active camber control		FW	FW - Smooth variable chamber		
Active landing gear					FW-Integrated brakes, nose wheel steering and rudder
Autoland	FW, RW	FW, RW			
Automatically reconfigurable control modes				FW-for pre-determined failure modes	

FW = Fixed wing
RW = Rotory wing

Figure 5-1 illustrates the state of the art in the higher levels of control system integration. It should be noted that this figure

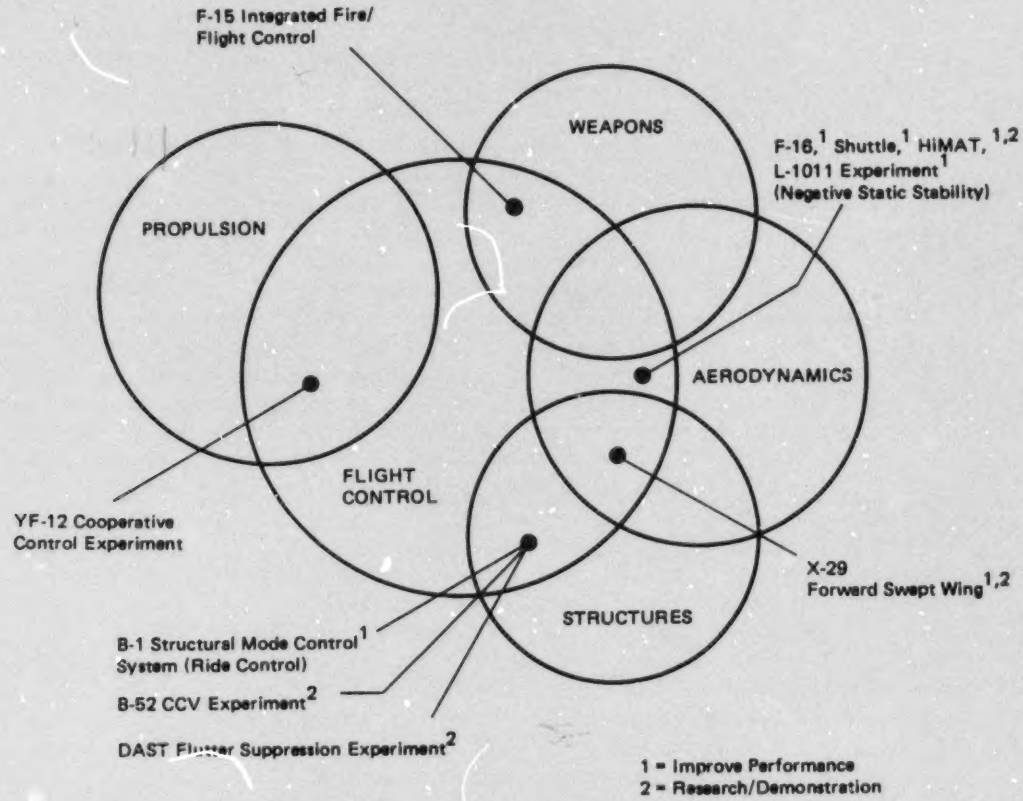

Figure 5-1 Control System Integration State of the Art

applies only to the major disciplinary areas. The intersections of these discipline areas represent functional integration as a design goal directed at new capability or improved performance. The F-16 and B-1 are examples of current production vehicles using integrated GNC systems. The other examples have occurred in research programs. These examples all successfully demonstrated the capability to achieve improved performance or effectiveness through integrated control.

The most significant barrier to full exploitation of integrated control is the extreme technical risk involved in the commitment to

such a design when considering factors as the wide range of uncertainties in aerodynamic, structural, propulsion, and environmental conditions for normal and failed flight conditions; the need for reliable and safe operations; and the economic or mission penalties for not achieving predicted performance in practice. The technical risk arises from the lack of design tools and models and lack of experience in actual application of tools in the real-world environment. Further information on structures as related to control systems is given in the report of the Panel on Structures (pp. 91-94).

Control System Architecture The architecture of a control system consists of the arrangement of its major elements and their interconnection, its hierarchy of operation, and method of functional implementation.

Architectural state of the art is summarized in Table 5-5. Generally, architecture has not been a limiting factor in the realization of flight control system functions to date. However, the projected character of the year 2000 GNC systems, which includes more complex, high bandwidth control, and includes more flight-crucial, life-critical functions, will stress current architecture design capability.

Control System Synthesis and Analysis Tools exist to support the design and analysis of complex feedback control systems. The state of the art allows multi-input, multi-output synthesis and analysis of linear continuous and discrete systems, with a large degree of computer-aided design and automation. Typical design practice involves use of optimal control methodology in the preliminary design phase, with final design taking place on batch and real time nonlinear, piloted simulation. However, system refinement generally is required in the flight test phase of a control system development.

The time and effort spent in the linear and nonlinear design phases are related to the state of development and reliability of simplified plant models. Also of importance are limitations in design techniques, specifically, the ability to deal with a large number of control effectors in highly interactive systems, and the ability to progress from state space synthesis methods to practical and realizable system designs.

Another more serious analysis limitation is the inability of even the best ground simulators to fully duplicate the pilot responses obtained in flight, especially for high-stress tasks that may lead to pilot-induced oscillations. Limitations in field of view, bandwidth and time delays in motion, and visual systems of ground-based simulators restrict the ability to predict consistently the pilot/system/vehicle responses encountered in flight.

Control System Components Current computer, sensor, and actuation system capability can be assessed by their ability to control functions and systems as noted in Table 5-4. The technology has

TABLE 5-5 Control System Architecture

Feature	Characteristics
Arrangement	Centralized computing for each system Limited multiprocessing Redundant channels Dedicated sensors for each system with limited shared use
Interconnection	Broadcast (civil) or multiplex (military) data base Hard-wired flight crucial sensors Fiber optics for interchannel communication
Hierarchy	Similar redundancy for normal operation Comparison monitoring with self check Dissimilar hardware/software for emergency operation Pilot oversight of system decisions
Implementation	Assembly language and high order languages Software intensive

advanced to the point where arrangements of these components can provide a level of integrity that results in probability of control loss of below 10^{-7} per flight hour for a 10 hour flight. Computational capability, sensor bandwidth and accuracy, and actuator bandwidth and force capability are able to handle control requirements over a wide range from small, low-speed drones to the space shuttle and high-speed missiles. Limitations in control system component technology are principally in the sensor area. Air data, angle of attack, and sideslip angle sensors tend to have excessive errors at extreme flight conditions or are not usable at all. In addition, sensor technology is lacking in the area of unobtrusive internal measurements for jet engines with closed-loop control.

Pilot Interface with Control Systems Crew commands are transmitted through force or deflection of center or sidestick controllers and through mechanical switches mounted on controllers or cockpit panels. Multifunction display/controls are used in both civil and military aircraft for mode or subsystem select functions. Control system operation may or may not be evident in control stick motion. Control system status in terms of channel operation is usually displayed normally to provide crew interaction with the redundancy management system. Helmet mounted sights and cursor control for military target designation are used operationally.

Limitations are principally in the area of pilot mode control of the systems. The ability of the pilot to command system functions rapidly and reliably in a high-workload environment is expected to be a problem unless man-machine interface and crew workload considerations become a more active, integral part of system design. Further information on the man-machine interface as related to control systems is given in the Human Factors Panel section of this report.

Projections to the Year 2000

Projections of technological advancements and their benefits and relevance in the guidance, navigation, and control disciplines are summarized in Table 5-6. It is expected that progress to the year 2000 can exceed linear extrapolation of current progress with appropriate support. The year 2000 technology projections expected to have the most impact on aeronautical science, technology, and ultimate aircraft performance and effectiveness are methodology for multidiscipline system integration; active subsystem controls; automated situational information management systems; systems, design and simulation of pilot/vehicle/interfaces; global cooperative airspace management; ultra fault-tolerant and reliable subsystems and systems; design- and validation-oriented software; onboard pilot/crew-aiding systems; GNC sensors; and aircraft power and control systems. Some detail on these selected projected technologies follows.

TABLE 5-6 GNC Technology Projections

Projection	Technological Impact	Benefits and Payoffs	Vehicle Class Relevance
Multidiscipline system integration methodology	Ability to optimize design of aircraft with highly integrated/ interactive aerodynamics, structures, propulsion, avionics, and control systems	o New aircraft capability - Low observability/high survivability - Supermaneuverability o Dramatic performance improvements through integration o Reduction in costly, inefficient iterations in development o Reduced overall system complexity o Drastically reduced risk in new airport development	o Enabling technology for: - Combat aircraft (fighters, multi-mission rotorcraft, and VTOL) - Advanced supersonic transports - Hypersonic and space airplanes o Improving subsonic transports
Active subsystem control	Ability to optimize design of individual subsystems	o Extract maximum performance from individual aircraft elements o Relax classical design constraints to boost performance o Provides reconfiguration options	o All aircraft
Automated situational information management system	Provide real-time situational awareness and action guidance	o Real-time civil or military mission optimization o Premission analysis/optimization o Optimal use of crew work capacity o Increased survivability	o Enabling technology for multimission combat rotorcraft and VTOL o Major improvements in combat aircraft o Civil aircraft
Pilot/vehicle/ systems interface design simulation	Provide means to optimize pilot interface with advanced vehicle systems	o Enhanced flight safety o Reduction in developmental iterations o Reduced development risk, cost o Higher-confidence simulation-derived requirements and assessments	o Applicable to all vehicle categories o Most important for: - Superaugmented aircraft (fighters, hypersonic and space airplanes, and advanced supersonic transports) - VTOL and multimission rotorcraft
Global cooperative airspace management	Capability for integrated worldwide air traffic surveillance, communication, and control	o Air traffic system optimization of time or fuel o Increased safety o Provides long-term growth/flexibility o Worldwide autonomous navigation to a few meters o Independent position information verification	o Major improvements in civil and military transport aircraft utilization o All aircraft

TABLE 5-6 (continued)

Projection	Technological Impact	Benefits and Payoffs	Vehicle Class Relevance
Ultra fault-tolerant and reliable systems	Architectures to support any aerospace vehicle configuration and mission	o Fault-tolerant systems o Dependable systems to support flight crucial active controls o Reconfiguration for damage	o VTOL, advanced fighters o All aircraft
Design- and validation-oriented software	Ability for designer to interface with software at higher level of abstraction	o Drastic reduction in software development cost o Nearly error free software o Simpler software mechanization o Preliminary design tool for software	o All aircraft
Onboard pilot/crew-aiding systems	Capability to carry and systematically access massive information data basis	o Single pilot operations in night/all weather for complex missions o Optimum use of crew work capacity and training time o Safe handling of emergencies	o Important for combat aircraft in high-pilot-workload mission phases o Civil and aircraft operations, training, and costs
GNC sensors	New class of GNC sensors for extending mission capability	o Dependable a/c sensing to support configurations optimized for observability o Obstacle sensing for nap-of-the-earth operation in night/all weather o Maximum utilization of pilot capacity through nontactile sensors	o Essential for some combat aircraft (fighters, bombers, cruise missiles) configurations o Essential for helicopters, VSTOL in IFR NOE
Aircraft power and control systems	Specialized actuation and power to implement integrated active controls	o Design option for all electric secondary power systems o No auxiliary bleed engines o Actuators for microcontrol o High-pressure hydraulics for weight, volume savings	o All aircraft

Multidiscipline System Integration Methodology

The most significant technology target for the year 2000 is the ability to design and deploy aircraft with highly integrated and interactive aircraft GNC systems. What will be needed are efficient design and analysis tools, trade criteria, and development experience. The aircraft design integration often will be driven and dominated by the GNC systems. The key technology then will be the multidisciplinary design of highly interactive aircraft subsystems for meeting classical civil and military performance requirements of speed, range, maneuverability, navigation, and efficiency, and new effectiveness parameters including observability and threat avoidance. It should be noted that severe design conflicts will arise and must be managed by this process. The payoff will be such things as the ability to

- o trade inherent natural stability and control of propulsion, structures, aerodynamics, with an integrated, automated GNC capability to reduce weight and drag or to provide new mission capability, i.e., low observability or "supermaneuverability." Involved would be such things as maneuver load control, gust load alleviation, active flutter suppression, and relaxed static stability;

- o integrate highly interactive subsystems such as vectored thrust and aerodynamic controls for trim, maneuver, and short takeoff and landing capability; and

- o integrate fire, flight, and propulsion system controls to maximize pilot/airplane capability to conduct complex attack/defense missions.

Effective design tools and criteria for highly integrated systems, possible by the year 2000, will have other dramatic effects on aircraft development. Such methodology will reduce the costly, time-consuming iterations that accompany new developments when adverse interactions are encountered or when performance goals are not met. In addition, the resultant aircraft subsystems and systems will require less redesign and refinement and thus be simpler, easier, and less costly over the life of the aircraft. This will reduce risk, development time, and cost of new aircraft, and will help ensure that predicted performance is achieved in practice.

Active Subsystem Controls

Not all of the benefits of advanced GNC systems will be achieved through integrated control. On-line, active control of individual aircraft subsystems or elements, in themselves, could improve significantly the performance of the aircraft. Digital electronic engine controls have reached operational status for both civil and military aircraft engines. These engines have increased operating envelopes,

reduced maintenance, and provided better airstart capability and more efficient operation. By the year 2000, more exacting control of internal engine operation could be possible. Direct measurement of critical performance parameters such as airflow, clearances, loads, and temperatures would provide the ability to better control engine performance for improved efficiency, reduced maintenance, and longer life while providing improved aircraft system performance. Further information on controls as related to propulsion systems is given in the report of the Panel on Propulsion (pp. 59-60).

Distributed control of aerodynamic shape could result in more direct, local flow control over major portions of the aircraft for reduced drag or flight attitude control. For example, internal actuators are being used to provide continuous, smooth, variable camber on an F-111 research aircraft. In some 15 years, it could be possible to provide local flow or vortex control over all lifting surfaces and portions of the fuselage to achieve optimal lift-to-drag ratios for cruise efficiency or optimal control for maneuvering flight.

By the year 2000, active structural system controls could be extended to provide self-adapting structural load accommodation through direct measurement and control of critical internal structural loads. This would allow tailoring the structural design for minimum weight through control of loads at key points in the structure to maximize aircraft load factor capability over its dynamic flight range.

Active subsystem controls can be thought of as "microcontrol systems" designed to extract the maximum performance from each aircraft element by allowing classical design constraints to be relaxed. This approach could provide unprecedented on-line optimization of individual subsystems as well as rich reconfiguration possibilities on new and existing aircraft.

Automated Situational Information Management System

By the year 2000 an automated situational information management system could be developed that would blend information on navigation, terrain, obstacles, threat, air traffic, and vehicle status and then generate trajectories or options for optimal mission effectiveness.

Complex aircraft and missions have created the need for integrating multiple source data from a range of sensors and information formats, i.e., radars, navigation, air data, flight control, and ground/airborne observation for presentation to the pilot for appropriate action.

Military manned or unmanned aircraft could benefit very appreciably from upgrading situation information and action technology. In the case of combat aircraft, vehicle status and threat situation, and optimal trajectory displays for attack or evasion could assist the

pilot under either manual or automatic control in achieving the mission with the highest possible probability of survival. Sensed information could be used in generating a "best" trajectory and presenting this information to the pilot through a panoramic cockpit display. This same blend of sensor information could be used to provide a tactical flight management capability for safe ingress, weapon delivery, and egress from enemy territory. In return to base, this system would use a blend of onboard and ground-based sensors to enable a safe landing on damaged runways.

For flights near the ground to reduce observability, navigation through passive sensors are the obvious preference. A typical tactical mission could involve an ingress and egress at very low altitude using terrain-following systems. Information regarding threats would be used to plan the route automatically. This mission planning would occur onboard with capability to replan the mission in response to new information. Thus, an automated planning and decision information capability would be an integral part of the navigation function that would make use of inertial, electromagnetic, and optical sensors, as well as radars and lasers that may operate in a covert fashion.

The sensor suite and associated onboard processing systems also would be capable of automatic target recognition. As the target is approached, the automated navigation function could plan the attack and could perform automatically the entire attack function. This will require a total blending of navigation, flight control, propulsion, and fire control information. Such a system would be capable of recognizing threats and taking automatic evasive actions if extremely short reaction time and narrow escape windows were required, as in the case of a surface-to-air or air-to-air missile attack.

The civilian navigation problem is less demanding, but it could benefit from the same technology. Path guidance in four dimensions would allow V/STOL aircraft to take maximum advantage of their unique capabilities in crowded metropolitan areas where precision navigation would be required. A planning function, much more extensive than contemporary flight management systems, could aid the crew in achieving highly efficient flight paths, avoiding the restrictions of current, predetermined air traffic control procedures.

The display technology projected by the year 2000 will greatly enhance the display of situational information. This includes panoramic perspective situation displays on "all glass" cockpit panels; ability to zoom perspective situation displays; automatic display presentation formats tailored to the mission, task, or threat; voice-commanded display formats; and integrated head-up, head-down, and helmet mounted sights and displays.

The payoffs here are real-time mission and trajectory optimization, and premission practice and analysis. Premission analysis would allow the development of tactics and the determination of probability of mission success. This would lead to increased survivability and reduced pilot workload in complex missions. These factors make this technology a key element in future aircraft design.

Pilot/Vehicle Interface: Systems, Design, Simulation

The pilot will be a key factor in mission success even though automated functions and systems become more important in achieving system efficiency and mission success. Given the complexity and capacity of the advanced aircraft and its mission, pilot-system interfaces are projected to become even more significant for reaching the full potential of mission and performance improvements.

In future aircraft, it could be possible to allocate man and machine roles and tasks optimally in the design stage. This is an important capability. It will allow designers to exploit advanced automated GNC systems while using the pilot in appropriate ways to enhance overall mission success and avoid undue workloads. For example, in pilot/-display/command architectural design, it should be possible to allocate roles and interfaces to minimize human error. System design capability could include rules for providing human and system "checks and balances" to ensure that neither human design, operator error, nor system faults produce catastrophic results that would have been avoidable through proper onboard actions. Further information on human/machine integration in aeronautical systems can be found in the report of the Human Factors Panel, pp. 182-184.

As the human role changes, modeling of the decision-making and dynamics factors can be expected to change. GNC systems will play a major role in minimizing complex, high-demand, high-stress situations. Because of this increased complexity, more importance will be attached to predicting high stress situations to allow sound advanced design decisions.

By the year 2000, it could be possible to tailor simulation models, visual scenes, and motion cues to ensure that assessments and evaluations are representative of actual flight and conservative at worst. This capability is important to the aircraft design problem, because even the best of this nation's simulators have failed to uncover critical vehicle/pilot/systems interface problems, resulting in operational problems and costly modifications.

Simulation technology advances in this area would lead directly to improved flight safety, reduced development time, and increased ability to optimize pilot/vehicle/systems designs prior to commitment to implementation in a vehicle.

Global Cooperative Airspace Management System

By the year 2000 it could be possible to have the capability for integrated worldwide air traffic surveillance, communication, and control. It should be noted that there is a strong interplay between the national airspace and commercial aircraft systems and their optimization. Manufacturers will continue to optimize and implement onboard systems that result in efficient operations in the air traffic control (ATC) system as it evolves.

Although a new National Airspace System plan is in progress, current air traffic control methodology is based largely on a predetermined finite set of network (airway) elements. This constrains the aircraft flow, creates aircraft traffic concentrations, and aircraft operating efficiency problems. Although current aircraft systems technology is capable of off-airway operations, control procedures and the structure of the present airspace system itself are unsuitable for nonstructured use. The present ATC system cannot fully exploit onboard GNC capability.

The sensor and data processing capability and cockpit displays of future advanced aircraft could provide the basis for permitting much improved pilot/crew situation awareness related to the aircraft flight path, airports and runways, airway routes, and severe weather. The ATC system of the next century is expected to provide aircraft with current weather and wind data, conflict alert information, and automated clearance and delivery information. Onboard processing and advanced data management techniques could be used to integrate this ground-based information with aircraft-derived data to provide a complete "picture" of the overall environment without adding to the pilot workload. Computed information on the aircraft of value to other aircraft or to the ATC system could be transmitted to ground stations for retransmission. This could result in improved traffic flow, reduced fuel consumption, and improved safety.

Appropriate civil aircraft could carry a worldwide terrain data base that could be presented on "all glass" cockpit displays which would show precise aircraft position with respect to the terrain. Systems would be capable of permitting the pilot to zoom in on specific terrain features to a precision of a few meters. Navigation could be achieved with navigation satellite systems and low-cost inertial smoothing. Obstacle warning worldwide also would be an inherent capability. Downlink and uplink transmission of all traffic within a specified radius could provide traffic presentation on a map display. Autonomous landing displays based on infrared or radar, projected on head-up displays, would be feasible. The system also could provide the means to deal with nonparticipating aircraft.

In addition, by judicious integration of digitally stored land mass data, inertial systems data, radar altimeters, and satellite signals,

a presentation could be generated in the crew station to provide self-contained autonomous precise navigation independent of ground-based information. A tactical fighter or commercial transport could navigate under conditions where ground updating was denied due to battle environment or loss of ground equipment.

The evolution toward this technology target has begun. New commercial transport aircraft recently introduced into airline service are equipped with Flight Management Systems (FMS) capable of 3-D navigation. Extension of this capability to 4-D area navigation will allow precise time control within the ATC system. Development of a satellite-based global cooperative ATC surveillance and communication system with surveillance commensurate with projected accuracies of the Global Positioning Satellite (GPS) would permit more closely spaced oceanic and continental routes, resulting in more efficient airspace use. This system could provide a flexible ATC process in terms of responsiveness to user requested changes in flight plans aimed at weather avoidance, preferred wind routes, and fuel savings. Such systems also have the potential for position accuracies sufficient for all-weather landings when used in conjunction with local differential corrections and inertial smoothing.

Closely associated with the GNC systems capability in enhancing the National Airspace System is the airport constraint. The ultimate constraining factor for airport capacity (and consequently delay times and fuel costs) is runway occupancy time or throughput. The runway management operations must be coordinated closely with the ATC to permit interweaving of departure aircraft with arrival aircraft. Improvements in runway throughput could be provided by advanced aircraft flight control systems and displays, along with ATC procedures for avoidance of wake vortices and provision for missed approaches and go-arounds. This activity has direct inputs to military field operations where diverse aircraft mix, runway denial conditions, and minimum fuel situations may exist.

Ultra Fault-Tolerant and Reliable Systems

Discussion has focused on advantages in performance, maneuverability, and low observability that can be gained by emphasizing those features in design without considering classical aircraft stability and system control constraints. The stability and control problems that result from this new emphasis will be addressed by complex multiple-redundant automatic flight control equipment which may activate a wide variety of control effectors (e.g., surfaces, nozzles, vanes, and jet flaps). For military aircraft with multirole missions, several effective vehicle configurations may be involved, especially when abnormal, emergency, or battle-damaged conditions are taken into account. The control equipment, therefore, must be redundant not only for flight safety, but also reconfigurable in the event of damage.

Incorporation of flight-critical active control technology such as relaxed static stability and flutter suppression in commercial transports would require full-time, full-authority fly-by-wire control. Whereas digital fly-by-wire control technology has been successfully applied to military aircraft, this technology is also being applied to commercial transportation to fully exploit the benefits of active controls.

In general, for an active control configured aircraft, the GNC system must be implemented so that flight and landing would not be compromised in the event of system failures when compared with a conventionally designed aircraft. In almost all active control applications that are seen as possible by the year 2000, the electronic control systems will be crucial to both safe flight and mission completion. By the year 2000, ultra fault-tolerant, reliable, and high-integrity flight control/avionics systems architectures could be available to support virtually any aerospace vehicle configuration and mission. Such architectures would be characterized by

- high-integrity, highly reliable, and highly capable processing systems that exploit on-chip redundancy and error correction capability;
- integrated redundant sensor subsystems with embedded fault reconfiguring processors to provide continuous sensor data under failed sensor conditions;
- reconfiguration capability to account for failures or damage not considered in the design; civil transports as well as military aircraft sustain damage or failures that have led to loss of manual control, and automatic control reconfiguration offers the potential for emergency operation following damage. For example, loss of an aerodynamic control surface could be automatically accommodated through coordinated use of remaining surfaces and the propulsion system;
- systems that provide growth capability without major redesign of the existing system. This suggests a system and software architecture with some degree of distributed processing;
- systems that are highly immune to electromagnetic disturbance either through the basic design or through alternate control paths (optical/fluidic);
- capacity to handle both low- and high-bandwidth control requirements;
- graceful degradation and automatic system reconfiguration to be nearly transparent to the pilot/crew; and

- features that allow the system to be easily verified, validated, and flight-qualified in a cost effective manner.

At the component or subsystem level, it should be possible to achieve operational optical fault-tolerant buses, full digital fly-by-wire control for civil transports, active flutter suppression for military aircraft with stores, and unified control laws adaptable to wide ranges of vehicle classes. The payoff of the technology will be dependable, cost-effective, fault-tolerant flight control systems able to implement the active controls necessary to achieve the desired performance benefits under normal and adverse conditions.

Design- and Validation-Oriented Software

Many functions performed by crews in current systems will be automated in future aircraft, placing far greater dependence upon the systems providing these functions. Thus, both manned and unmanned vehicles will be far more dependent on the onboard systems than is currently the case. This high level of dependence implies the need for extremely high reliability and availability of these systems. Fault-tolerance, as it relates to sensors, actuators, signal processing, data processing, memories and software, will be the key to achieving required operational reliability.

A critical factor in implementing advanced GNC functions is software. Software technology will be an enabling element of the systems projected for the next century.

The year 2000 software process could dramatically change the way system design and development proceed. New GNC specification languages could allow functional requirements to be translated into software specifications at a higher and, therefore, more understandable level of abstraction. This would, in turn, allow the actual code to be generated from higher level, complete, and nonambiguous specifications. In addition, software design methods and tools could be in hand that would ease the testing of complex systems.

Today, specification, verification, and validation are highly subjective tasks. In the next 15 years, it could be possible to generate a verification test matrix based on the software specification, thus providing a high degree of objectivity and automation in the test process. The payoff of this year 2000 process would be significant reductions in development costs of complex software, the production of higher integrity (more nearly errorfree) software, simpler software mechanizations, and high-level software representations for preliminary design trades.

Technology advances in the software area are crucial because the projected software burden for next-century GNC systems is staggering.

It is vital for the success of advanced GNC technology that the technical community be able to deal with this volume and complexity of software by the year 2000.

Onboard Aiding Systems

By the year 2000, it could be possible to carry and access intelligently, massive onboard data bases to aid the pilot and crew in mission conduct, tactics, and vehicle system management.

Both manned and autonomous vehicles will have extensive onboard computing capability to provide most, if not all, operational functions. Aspects of "artificial intelligence" show promise in mechanization strategies, with "expert" system methods the most promising current area of application in tactics and vehicle systems management. The GNC demands of real-time expert systems operations may well drive this technology.

High-speed solutions of complex algorithms could define options for piloted or automated systems in the selection of trajectories for maximum success in combat. Helicopter pilot workload already is staggering in nap-of-the-earth missions. This technology could permit single pilot operation in complex missions. The air-to-air problem, involving multiple threats and friendly aircraft, could take into account aircraft lethality, as well as position, to determine the targets, method of attack, and deployment of aircraft. The air-to-ground problem similarly could take into account targets and threats, as well as cooperation with friendly aircraft and troops. Rules of engagement would be included.

Onboard aiding in trajectory determination could find application in transatmospheric vehicles that would have complex ground track, heating, and range constraints. For civil aircraft, "tactics" would include trajectory selection modified by winds, ATC restrictions, aircraft configuration, and emergency conditions. In the realm of vehicle systems management, onboard aiding could provide "expert copilot" assistance in handling abnormal or emergency conditions.

The integrated system architectures of the year 2000 will prove too complex for manual management. Onboard aiding appears to be the most reasonable compromise between manual and fully automated systems.

The payoffs will include the ability to conduct more complex missions, i.e., night/all weather conditions; optimum use of pilot and systems capability; optimum use of training time; effective and safe handling of aircraft emergencies; and reduction in the incidence or impact of human error.

A key element in onboard aiding is onboard data management and processing. Data and signal processing, data transmission rates, and memory capability requirements for these advanced systems are well beyond current state of the art, but should be available in the year 2000.

It should be noted that there are a great number of important implementation issues related to advanced GNC systems, but with the level of detail dictated by the limited time available at the workshop, it was not possible to discuss all such factors.

Optimized GNC Sensors

New classes of sensors for GNC are possible by the year 2000. Several examples illustrate the range of sensor technology advances that can be projected.

Helicopters face severe hazards and related operational constraints in near-ground operations, a major problem for both civil and military missions. Sensing of small but potentially catastrophic obstacles, such as wires, is needed to help ensure safety of flight at low altitudes, at low speed and under high-speed maneuvering conditions.

In another area, major advantages in performance, maneuverability, and low observability can be gained by optimizing aircraft performance at the expense of classical constraints and then relying on automatic flight-control systems. Resulting configurations often lack lateral and longitudinal stability and have poor flying qualities. Such deficiencies can be corrected with automatic flight controls that will consist typically of multiple-redundant equipment for flight safety. Sensor and associated computational arrays are key elements in this complex equipment. At present, the sensing, on a multiple-redundant basis, of angle of sideslip is seldom feasible on operational aircraft, yet these parameters are extremely useful in correcting unfavorable dihedral effects and in increasing directional stability.

In order to implement the active subsystem controls, direct measure sensors are required to allow the implementation of "microcontrol systems." Such sensors would be used to measure local pressures, temperatures, clearances, vibration, fluid condition, surface condition (roughness, dirt), strain, flow vorticity, deflections, and external disturbances. Application of embedded computing capability in these sensor subsystems could provide a new dimension in distributed system control.

Another dimension of sensing is that of nontactile sensors for pilot commands. Increasingly complex man-machine interfaces and demanding operating environments, e.g., high-g, fuselage pointing, and other unorthodox flying techniques, motivate the need for alternatives to

control sticks, buttons, and knobs to transmit command information from human operators to the GNC system.

The types of situational management systems discussed previously call for technology developments in helmet mounted displays and eye movement sensors for the combat arena. Here action against multiple targets in a single pass could be enhanced through the use of pilot eye movements/orientation in the serial selection of targets and weapon launching.

Another sensor technology that would have a significant impact would be command sensors sensitive to continuous speech rather than only to word commands. This could aid the pilot in the conduct of complex night/all weather missions by reducing the amount of manual interface with aircraft systems.

Individually and collectively, there can be dramatic, reliable extensions of current aircraft mission capability through the development and application of these technologies.

Aircraft Power and Actuation Systems

By the year 2000, it could be possible to develop new classes of actuators and power systems to support the highly interactive, integrated control systems projected for the next century.

New actuation systems will be required to reach the potential of dispersed control for local aerodynamic control or structural load control or for microcontrol of internal engine functions. These actuators could be small with high-bandwidth and rate capabilities and be able to be linked in networks.

Although hydraulics have provided excellent performance, there is the promise that elimination of electrohydraulics can be a major step toward achieving higher overall system reliability. High-voltage electrical power can provide more flexibility and be more accommodating to the types of redundant flight control architectures that technology development will allow for future aircraft.

The payoffs of the all-electric aircraft and its secondary power system could be improved propulsion system performance through reduced demand for, or elimination of, auxiliary engine bleed; reduced aircraft weight due to subsystem weight reduction; and a more unified and integrated aircraft power system with the potential for increased integrity, fault-tolerance, and simplicity. However, high-pressure hydraulic systems (4000 to 8000 psi) also could provide benefits in terms of weight savings and size, and it is expected that hydraulic systems will continue to see extensive use.

A simple summary listing possible future research and technology supporting activity and needs is included in the appendix. The panel believes that this kind of activity is needed to make it possible to realize the advanced performance discussed in this report.

Report of the Panel on

Computer and Information Technology

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Ronald L. Larsen, Rapporteur

COMPUTER AND INFORMATION TECHNOLOGY

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COMPUTER AND INFORMATION TECHNOLOGY

Introduction

Aircraft have become more and more dependent on computers (information processing) for improved performance and safety. It is clear that this activity will grow, since information processing technology has advanced by a factor of 10 every 5 years for the past 35 years and will continue to do so. Breakthroughs in device technology, from vacuum tubes through transistors to integrated circuits, contribute to this rapid pace. This progress is nearly matched by similar, though not as dramatic, advances in numerical software and algorithms. Progress has not been easy. Many technical and nontechnical challenges were surmounted. The outlook is for continued growth in capability but will require surmounting new challenges.

The technology forecast presented in this report has been developed by extrapolating current trends and assessing the possibilities of several high-risk research topics. In the process, critical problem areas that require research and development emphasis have been identified. The outlook assumes a positive perspective; the projected capabilities are possible by the year 2000, and adequate resources will be made available to achieve them.

Computer and information technology forecasts and the potential impacts of this technology on aeronautics are identified. Critical issues and technical challenges underlying the achievement of forecasted performance and benefits are addressed.

Technology Forecast

The panel believes that the general technological progress through the end of the century can continue at the pace experienced in recent years. In general, the richness of the processing environment available to aeronautics applications likely could exceed what the aeronautics industry will need or be ready to absorb. The following sections discuss the technology forecast, both in terms of what technology will be available and in terms of technical barriers and research challenges.

Microelectronics

Microelectronics technology may be nearing the end of its period of exponential growth. While technology advances are expected to continue until the end of this decade, by the late 1980s or early 1990s the projected physical limits that affect the implementation of VLSIC will have been reached. Current field effect transistor (FET)

geometry cannot be scaled below approximately 0.25 micron. The steady rate in which the feature size of devices is shrinking will level off before hitting this limit. In order to sustain the growth projected, new microelectronics techniques must be developed. At present, the most promising are

- "3-D" (high rise) circuits (circuits built on top of other circuits);
- modular digital function devices that accomplish more complex functions than current logic elements (needed in order to minimize interconnections); and
- significant, new, digital integrated circuit technology, involving submicron structures and exploiting physical principles not currently utilized in integrated circuits, which can be scaled to the limits of fundamental physical laws, and which solve the interconnect problem.

These continuing advances lead to more and more complex digital integrated circuits. Because a large percentage of the functions of a system will be included within just one "chip," the approach to designing these components will be accompanied by a high degree of integration in the total system. Internal self-testing and other capabilities that contribute to high integrity will be included in the design of each chip. While these components will be extremely complex, the semiconductor manufacturers will attempt to find special products where the development investment can be amortized over large manufacturing volumes. However, parts needed by the aeronautics industry are not likely to represent a major demand on any semiconductor vendor. In order to make best use of standard parts, the aeronautics industry could specialize the application of general processing parts through the use of software. Current efforts within the semiconductor industry to establish silicon foundries, which will be able to provide fabrication support for a wide mix of semiconductor designs, each of which might represent a very small production volume, should be supported actively by the aeronautics industry. An active, viable industry of this sort will be important to the aeronautics industry so that there will be appropriate utilization of advanced microelectronics technologies. Such an industry also would support on-demand fabrication of spare parts.

Future aeronautics products would require special component capabilities. One of the most stringent requirements involves very high-temperature devices for engine sensors and controls. Such specialty devices will not be a priority project in the computing/semiconductor industry without incentives from the aeronautics industry.

Components

Rapid advances in processing and storage device technology are expected to continue. Logic and memory component density, increasing by a factor of 10 every five years, is expected to continue to increase through the end of the century. Manufacturing cost per chip will begin to increase as feature size moves down to the fractional micron domain, but cost per unit capability will continue to decline. Mass storage capacity exhibits a similar but slower trend than semiconductor technology. Magnetic storage density has been increasing by a factor of 4 every five years, a trend expected to continue. Rotating magnetic storage is extremely difficult to package for airborne application. Often magnetic tape storage must be used, at a greater performance penalty. Current optical storage technology provides approximately an order of magnitude increase in system capacity per unit volume. Its storage density is expected to increase at a rate slightly slower than that for magnetic technology. Video disk technology represents another possible hope for the future. Two hours of video is more than 500 Gbits of storage. As this technology is adapted for use in digital systems, the problems of how to store the very large raw data arrays from simulations, for example, may be ameliorated.

Frequency division multiplexing techniques on optical fibers will enable up to 50 channels, each of 0.5 to 1 gigabit per second bandwidth, on a single optical fiber. Optical bus systems will be capable of supporting at least 64 taps over buses up to 1 km in length.

Many new sensor capabilities will be available by the end of the century, including solid-state sensors where processing and memory would be integrated with the same devices as the sensors. New chip-level and wafer-level interconnection technologies, such as holographic techniques, will be in use to alleviate many of the component level interconnection problems.

Processor Organization

The von Neumann architecture, which has been the dominant model for computing machines to this time, is limited inherently by its sequential operation. Maximum performance is bounded by the machine's cycle time, which in turn is bounded by the propagation time of signals. The propagation time of signals is expected to inhibit clock periods shorter than 1 nsec. Thus, the maximum performance achievable by these machines appears to be 10^9 instructions per second. To advance dramatically beyond this point will require parallel architectures. By the year 2000, effective parallel architectures employing thousands of processors, high-bandwidth communications, and distributed software will be readily available. These architectures will incorporate cooperating clusters of processors and with local control of subsystem resources.

System and Subsystem Architecture

Some subsystems will be general purpose and some will perform algorithmically specialized functions such as signal processing, data base management, and flow model processing. By the year 2000, such functions will become more general and the cost/performance or size/performance will be improved by factors of 2 to 3 orders of magnitude, primarily through the use of parallel and distributed architectures.

Computing systems capable of up to 1000 GFLOPS (billions of floating point operations per second) and containing up to 10 Gwords of random access memory (RAM) will be in use by the designers of aeronautical products at the end of the century. Information management and symbolic processing functions will be integrated with numeric computation, and be adapted for limited real-time applications. A range of capability will be available to support new parallel algorithms.

Smaller-scale multiprocessors will control high-performance, graphics-oriented design and modeling workstations that would be connected to the large-scale systems. These workstations will be capable of adapting easily both to various usage disciplines and to individual users. The workstations themselves will have computational power in the 100 to 1,000 MIPS range on 32-bit operands. The workstations are expected to contain up to 50 Mwords of random access storage. Rotating storage will be either optical or a combination of optical and magnetic with 10 to 100 gigabyte capacity. Workstation displays will have special hardware for dynamic manipulation of full color images with resolution of up to 8K x 8K pixels. These workstations will be capable of close interaction with a distributed system environment and will seem to be a local extension of the high-performance computing systems.

Systems with real-time requirements, such as airborne computing systems and ground-based command and control systems, will be highly distributed also. Highly reliable processing capabilities will be synthesized from both general purpose processors (where each processor will be capable of executing at rates up to 1,000 MIPS and contain up to 50 Mwords of RAM) and algorithmically specialized processors. The sensor and effector subsystems will have integrated processing power allowing direct implementation of many capabilities which today are accomplished in separate interface subsystems. These capabilities will include transforming data to standard formats, interfacing with a communication network, and performing fault detection and isolation. The elements of these dependable airborne systems (including sensors, processors, and effectors) will be interconnected with networks consisting of redundant fiber optics paths.

First of all, even though very high speed arithmetic elements will be available (possibly utilizing optical processing technology), the most advanced processing systems will continue to be constrained by memory capacity and access times. Memory capacity will be limited by component technology, especially for nonvolatile memories. Memory access times will be subject to the limitations inherent in large addressing structures. Significant improvements in memory bandwidths will be required in order to field the high-performance systems projected. Because of the broad parallelism expected in the systems of the future, large high-bandwidth interconnection networks to provide high-performance transfer paths among the processors and memories will be needed.

Integrity would be achieved through integrated hardware/software fault tolerance, reconfiguration procedures, and robust architectures that can continue to function in the presence of error conditions. Subsystem performance and error monitoring would be integral to the subsystem design and implementation. Close to 100 percent availability of processing capability together with near zero unscheduled maintenance support would be achievable because the density of components would allow the inclusion of the redundancy necessary to implement high levels of reliability at marginal added production cost. System level procedures, with data gathered from integrated component-level monitors, would forecast incipient failures. Systems would incorporate maintenance and diagnostic aids capable of guiding average-skill-level maintenance personnel to perform quickly scheduled maintenance subject to a set of field resource constraints (time, tools, spare parts, etc.).

Software

By the year 2000, some basic algorithms for effective management of parallel and distributed architectures will be in place and will be used widely in high-performance system architectures. Parallel algorithms for highly structured types of processing such as linear algebra and image processing will be available. New approaches to the description of processes to be performed would facilitate the use of large-scale parallelism and would speed the integration of communications and information management capabilities within these high-performance systems to support much more flexible modeling of real-world situations.

The software tools available to advanced, large-scale mathematical modeling activities that are an integral part of advanced aeronautical research programs would include high-level, working environments tailored closely to the particular discipline and the work needs of the researchers. These environments would integrate the capabilities of the high-performance workstations and the computing systems

described earlier. Software would support high-performance evaluation of complex symbolic mathematics. Even today complex algebraic expressions, derivatives, and integrals can be evaluated quickly and easily. Progress will be rapid once such systems are used widely.

The efficient utilization of the high-performance processing capabilities would fall largely to the software developers. Performance and utilization issues will become an even more important part of the total development process from the original specification through algorithm development to software engineering and implementation. The major, common thread through these areas is the urgent need to manage complexity better.

Artificial Intelligence and Expert Systems

Artificial intelligence is an area of great publicity at the time of this report. The technology for implementing semi-intelligent subsystems will be in place by the end of this century and will be available for application to aeronautical system products and development processes.

Expert Systems One type of semi-intelligent systems, the expert system, is available and is able to reason using a set of facts and rules. The expert system consists of an "inference engine" which is used to interpret the current situation based on facts (current inputs) in the "situation base" and on rules which describe dependencies and relationships in the "knowledge base." Given the facts and the rules, inference engines can logically analyze a situation and also can "explain" how they reached the conclusions presented. The major difficulty in application of expert systems is the same as that encountered in the design of any large system--the need for complete specification. Rather than provide a complete definition of all legal states together with some state transfer diagram which explicitly defines all possible transfers between states, an expert system uses a complete set of rules that together explains how to find all legal states and how to determine what transfers are legal between states. Thus, use of an expert system requires a domain of knowledge that must be well defined and codifiable. By the end of the century, specialized expert subsystems will be in common use and will contain regularly from a few hundred up to several thousand facts and rules. In future expert systems, users will be able to modify a system by adding to or modifying the rules and facts in the knowledge bases.

The most significant advances in expert systems technology are not likely to be in the execution mechanisms, but rather in how to acquire and organize knowledge about the various domains where the systems are to be applied. These advances address the current bottleneck to the

use of expert systems, the manual acquisition organization, and structuring of the knowledge base. This activity is currently very tedious, involving many man-years of effort to develop a knowledge base on the order of 1,000 rules. Expert systems now under development will not scale indefinitely to very large knowledge bases and application domains. Expert systems can be implemented for applications limited in scope, which can have their facts and rules (or relationships) explicitly defined and codified. Application of expert subsystems, each of limited scope, within a highly distributed, multifunctional airborne environment is most likely. The use of such systems today are restricted to non-time-critical applications. By the year 2000, expert systems will be applied to real-time applications with moderate sized knowledge bases. In applicable problem domains, expert systems will reduce significantly the effort required to field a system.

The terms artificial intelligence and expert systems easily can be misunderstood by those not acquainted with these technologies and can lead to misapplication. As with any system, an expert system will be capable of accomplishing only what its designer/expert imparts to it. Thus, the problems of translating a particular discipline into a knowledge base to be used by an expert system are very deliberate and painstaking, with structure and quantification being applied to areas that often have never been thought of in those ways before. The complexity involved in developing such knowledge bases seems to scale nonlinearly. The divergence in the rate of improvement in the ability of equipment to support complexity compared to the growth of application complexity could prevent indefinite scaling of these systems.

Theorem Provers Another type of semi-intelligent system is one that, when given a set of hypotheses and a proposed theorem, will aid a person in developing a proof for the theorem (if possible) or in constructing a counterexample to disprove the proposed theorem and guide the development of a correct theorem or set of hypotheses.

The area of theorem-proving systems (hardware and/or software) has had few practical successes and many failures. However, the details of current designs of commercial large scale integration (LSI) devices are being verified before the chips for their implementation are produced. This has proven to be the most effective way to maintain a reasonable schedule for system deployment and initial validation and verification. With the advent of VLSI, validation and verification are much more necessary (turn-around time for changes to chip design and the fabrication of chips will take longer), but the difficulties are much greater. Currently, work is progressing slowly since failures in practical verification have been the rule rather than the exception. However, this work needs to proceed.

New, higher-level programming languages, easily accessible libraries of theorems previously proved, and techniques for handling such logic data will facilitate using a computer to prove difficult theorems in these areas. As in the area of expert systems, theorem provers will not solve arbitrarily general or complex problems, but will find acceptance in certain well-defined, limited domains.

Other areas of artificial intelligence are under development and are expected to result in new technologies that would be beneficial to the aeronautics community. These include

- o robotics
- o goal seeking and reasoning systems
- o vision
- o speech recognition
- o natural language understanding

Man-Machine Interface

By the year 2000, the functionality and speed of computer and information technology would be utilized to augment significantly the capability of the users. For example, in airborne systems, the information available from onboard sensors, from stored knowledge, and from observation of and interaction with the flight crew would result in presentation of timely and pertinent information to support effective total situation comprehension by the flight crew. In many respects, such an advanced man-machine interface would be perceived by the flight crew to be nearly as helpful as the ideal flight instructor. By considering the ever-changing situation and by presenting only that information pertinent to a given situation, the future man-machine interfaces would allow the user to focus on the decision process, exception handling, and strategy development and implementation. Further information on the human factors aspects of the man-machine interface as related to control systems is given in the report of the Panel on Human Factors (pp. 182-184).

System Development and Implementation

As a result of advances in distributed systems by the end of the century, integrated aeronautics system design, development, and manufacturing systems will be feasible, eliminating the need for large, centralized systems. These integrated aeronautics development systems will include

- o multidisciplinary design tools accessible through advanced workstations;

- integrated data bases including capabilities for sharing and for distributing the data effectively;

- sophisticated configuration control support including the integration of such support with the design tools, with manufacturing and inventory control, and with other important aspects of system development including communications with users;

- verification and validation capabilities to allow significant improvements in the confidence level associated with a given design; and

- testing capabilities that include sophisticated test and diagnostic generation techniques.

Such a highly integrated system would provide the flexibility to control rapid variations in manufacturing demands that are especially important in being able to mix a variety of products on one line. Computational equipment and sensor technology would be integrated into numerically controlled machining and manufacturing systems. Mechanical fabrication of parts to better than a 1 micron manufacturing tolerance would be achievable by the end of the century.

High Integrity

A major system objective for advanced computing systems is high integrity within the system. Major advances in components, architecture, software, algorithms, and human interfaces are required. Components and architecture are likely to progress sufficiently without aggressive efforts by the aeronautics community. A significant amount of research and development will be needed in the area of fault-tolerant multiprocessors. Aeronautics requirements for software, algorithms, and human interfaces are complex and critical and will require special attention. The application of sophisticated expert systems in airborne environments will be limited by uncertainties in the integrity of such systems rather than by the functionality of those systems. New architectural ideas, for example, are advancing far more rapidly than evaluation and verification and validation technology. How to determine that a complex software system does what it is intended to do is an unsolved problem in almost all cases. The current state of the art in verification and validation is inadequate for advanced architectures.

A theory and methodology encompassing proving and testing is required. Effective resolution techniques in the presence of ambiguity and uncertainty must be provided. Such work is time-intensive, requiring early attention.

Technical Barriers and Research Challenges

The major impediment to full utilization of computer and information technology is expected to be its assimilation into engineering practice. The most critical technical impediments will be size/performance, dependability, and management of complexity. The major challenges are likely to be encountered in the areas of software development, system verification and validation, communication and control, and programs designed to augment human intelligence, such as expert systems, theorem proving, and symbolic mathematics.

The size of the market for computers in aeronautics is small in comparison with the data processing/business market. Thus, the unique requirements of aeronautics will receive little attention from the industrial community without special attention and incentives. Those aspects of general computer and information technology development that are most critical to aeronautics applications should be identified and stimulated, and progress carefully monitored. A summary list of the most critical technical barriers and research challenges is contained in the appendix.

Projected Impact of Computer and Information Technology on Aeronautics

Computer and information technology is a supporting and enabling technology to the aeronautics industry. The projections discussed concentrate on the impact of computer and information technology on the technical aspects of this industry.

A few examples are discussed below to set the technology forecast in an appropriate application setting.

Development Process

Today's product development period is characterized by the delivery and coordination of requirements, specifications, and test data across numerous organizational interfaces. The availability of a comprehensive, integrated product data base (and associated computer-based support tools) to those in the development process will accelerate the product development significantly. Integrated computer-aided design/manufacturing/test distributed systems, coupled with major improvements in data management and computing performance, will reduce greatly the need to prepare and transfer documentation between organizational and functional units. A "product" data base would be formed at the conceptual stage and would be refined and extended continually through the design, test, manufacturing, and maintenance stages. The data base also would serve as the product's

history for maintenance purposes (recording failures, replacements, engineering change status, etc.).

A reduction of the current 15-year development period for major new aeronautical products to 12 years or less can be achieved by the year 2000. Such an improvement in productivity would enable the development of advanced aircraft that otherwise would not be possible economically or strategically. Improvements in formal specification languages and incremental verification and validation procedures would allow these aircraft to use electronic technology which is state of the art a few years before the aircraft is shipped, rather than obsolescent electronics available earlier in the design cycle.

A key element of the integrated product data base is distributed workstations capable of supporting the design activities. Designers would have local processing power in a design center (currently called a workstation) comparable to the highest performance supercomputers of today. These high-performance design centers would combine numerical computational capabilities with symbolic computations, sophisticated displays, and image processing. These design centers would themselves be part of a larger distributed system consisting of other design centers and advanced supercomputers.

Advanced Aeronautics Research

Computer and information technology would not only impact the products of the future, but would also contribute to major advances in aeronautics research itself. By the end of the century, computational power will be available in a much different form than it is today. Researchers will have significant local processing power in the advanced design centers. These design centers would provide significant leverage to researchers studying combustion models, turbulence, structures, chemical properties of advanced materials, advanced CFD, and nonlinear, multivariable optimization. Further information on computational technology as related to aeronautical structures is given in the report of the Panel on Structures (pp. 91-94).

Remotely Piloted Vehicles

Improved remotely piloted, semiautonomous and autonomous vehicles to perform missions unsuited for manned aircraft will be possible through the application of computer and information technology. Examples include vehicle missions that require very long endurance (e.g., communication relays and fire control) and military missions such as defense suppression too dangerous for manned aircraft. In military applications, the communication links may be severed for extended times, requiring the unmanned vehicle to operate autonomously

for those periods. The technology necessary to meet this objective includes smart sensor control and processing, and improved capability for remote control. Advanced system approaches would allow these requirements to be met by reducing the control bandwidth. A single mother aircraft would be able to control several vehicles that independently respond to threats and target opportunities.

Airborne Systems

The generic airborne avionic/control system is composed of sensors, processors and effectors, where sensors include flight and maintenance crew input transducers, and effectors include crew displays. The airborne system architecture of the year 2000 will have specialized processing capabilities distributed to the sites of sensors and effectors. The majority of the application code for avionics and controls would be executed in a cluster of processing resources that are autonomous with respect to their unique, core tasks, but cooperative with respect to systemwide functions such as fault isolation and maintenance diagnostics. These systems would be capable of reconfiguration of resources when necessary to maintain flight critical services. Some of the processors that would be utilized in these airborne systems would be able to provide the computational capabilities of today's supercomputers. System dependability would be achieved by inherent subsystem and component reliability combined with hierarchical fault tolerance. Predictive monitors would be used to forecast incipient failures and set in motion corrective action that would allow the reduction of unscheduled maintenance to near zero.

Crew Interfaces

Research work now in progress promises to revolutionize the avionic/control system interfaces with both the flight and ground crews, especially in the arena of detecting, interpreting, and responding to in-flight faults and failures. Future crew stations are expected to include new technology to improve materially the performance of the flight crew in evaluating mission alternatives in the face of such events, and of the ground maintenance crew in carrying out repair, especially in adverse environments. The anticipated computation-rich airborne environment would support a new kind of man-machine interface designed to facilitate situation comprehension by the crew. Efficient situation comprehension would be achieved by the use of computers to integrate all available data from the entire system. Information delivery tools, including visual, audio and tactile devices, would be designed with emphasis on information presentation and comprehension, not just data-delivery. Speech would seem intelligent, and information presentation would be in a format responsive to the preference of crews, both in choice of what is to be presented and in the form of presentation. The

resulting system would be capable of analyzing the dynamic situation and presenting the information such that it would be easily comprehended and the crew would be able to concentrate on critical decisions and the course of action.

Critical Issues

Scientific Supercomputers and Their Applications

The development and use of scientific supercomputers is an urgent issue to reaching the full potential of aeronautics in the United States. The development of the supercomputers themselves will tax technology on many fronts, from components, to system architecture, to software. The availability of new generations of supercomputers and new architectural concepts used to deliver their capabilities requires that the user communities develop new algorithms and computational models in order to achieve the opportunities and speed presented by these machines.

Scientific Supercomputers With the increased availability of processing resources and with the rapid progress of CFD algorithms, advanced supercomputers are expected to be capable of studying physical effects that currently cannot be studied either experimentally or computationally. The first generation of these advanced supercomputers is likely to be networks of tightly coupled processors, working in parallel on a single problem, in the MIMD (multiple instruction, multiple data streams) mode. Neither software technology nor algorithms are capable yet of dealing with general structures of multiprocessors for nontrivial problems. CFD is, fortunately, a relatively well-structured problem area and is included in the family of problems that will benefit tremendously from the ability to utilize such supercomputers. A recent National Research Council (1983) report (The Influence of Computational Fluid Dynamics on Experimental Aerospace Facilities, A Fifteen Year Projection) which was prepared by the Committee on Computational Aerodynamics Simulation Technology Development contains some details concerning this area, including detailed technology forecasts. Appendix B of that report ("Microelectronics and the Supercomputer Industry through 1995" by Sidney Fernbach) is especially pertinent.

Advanced supercomputers will need new approaches to dealing with possible faults in highly parallel systems. Present approaches to fault recovery do not seem to scale with fidelity. Approaches based on error correction/detection at lower levels must be developed in order to field systems that users will consider trustworthy.

An approach at the low level is the application of redundant coding of the digits used in the computation. A different approach is to

develop checking algorithms which work at much higher levels than today's algorithms.

There are many well-known redundant relationships among mathematical entities that are not used today for checking, because performing these checks would necessitate a checking computation that is problem-specific and also expensive in dedicated hardware and time. When hundreds of processors are being used on a single problem, some can be used on various parts of the problem, (usually to increase performance), while other processors, programs, and communication devices would be used to determine that the computation is correct.

While advanced supercomputers will be critical to the projected advances in aeronautics, the market for such advanced supercomputers in the aeronautics industry is so small, and the development time and expense is so large that CFD, in itself, may not provide the justification for the needed commercial developments to reach these capabilities. The designers of these advanced supercomputers need some means to have their design experiments (early prototypes) used and evaluated within the aeronautics community in order that such experience can be factored quickly into final product designs. Because the use of these advanced supercomputers is critical to reaching the capabilities of aeronautics technology outlined in this workshop, concern about loss of U.S. preeminence in this area has been growing. This problem is discussed further in report cited in the bibliography on the subject of supercomputers.

Large-Scale Computational Modeling Computational modeling of physical systems, principally fluid dynamics and structural mechanics, will be activities that benefit from the projected growth in supercomputer capacity. In this area, a large amount of parallel computation exists, is easy to discover, and is relatively easy to exploit. The impact of a 100 to 1,000 increase in computer capacity would be to bring detailed 3-D analysis from the research stage to a routine design procedure. Detailed projections of computational mechanics capabilities and applications areas have been made in other studies--National Research Council projections, for example--and are not repeated here. The amount of computation capacity available for research computation would be large enough to suggest that a principal factor limiting their usefulness will be the ability to interact effectively with computed solutions.

The computational fluid dynamics methods that supercomputers of the year 2000 could support would provide the opportunity to improve the understanding of both internal and external airflows. Improved structure analysis methods also would be permitted by the increased computer power in the year 2000. Such computational models provide insight into physical phenomena unobservable directly through physical experimentation, enabling the design of aeronautical systems otherwise unattainable. Validation of the underlying models and theories

becomes a critical issue. With high-performance computers and validated models, more efficient or higher-performance aircraft and propulsion systems can be designed. In addition, these methods would be coupled with nonlinear, multivariable optimization techniques to automate further the design process. Also, it would be possible to integrate the numerical simulation of multiple disciplines such as computational fluid dynamics and structural analysis facilitating the development of better-integrated designs.

High-Integrity Distributed Systems and Their Utilization

Airborne computational systems of the future will depend on distributed systems of high integrity to deliver the required functions. While the computer science community is studying distributed processing, the challenges of an airborne environment are sufficiently unique that the aeronautics community should be motivating special consideration to their problems. In particular, some issues critical to the implementation of airborne systems are the high integrity required (a subject that includes the need for redundant paths in interconnection networks and the need to monitor components actively in order to provide predictive maintenance capabilities), the need for processing sites of widely varying capabilities within the system, and the need to understand the real-time control capabilities of such distributed systems. The design of large, complex, distributed systems also must be understood, since the division of work in the implementation of such systems may be different from central controller systems.

Aeronautical computers that perform flight-critical functions would need to have a probability of failure (no loss of a sufficient performance level) of 10^{-9} for short periods (10 to 20 hours). Then rapid, but thorough, revalidation is necessary so that repairs can be performed not only for the faults that caused detected errors during the previous flight, but to determine the presence of previously undetected thats which might cause errors during the next flight. Commercial computing systems need high availability also, but only of a magnitude of 99.99 over much longer periods of time. Short periods (a few minutes) of downtime can be tolerated, if immediate rapid repair is available. If the expense warrants it, on-site personnel can be made available as necessary. Graceful degradation to a minimum service (unacceptable for more than a few hours) is another possible option. Thus, the aeronautical and commercial requirements are very different. Both requirements have validation and verification problems, but those of aeronautical systems are not only more severe, they are distinct from those of the commercial world. Thus, proper validation and verification procedures for aeronautics would not be considered as part of the techniques being developed for commercial computer systems. Validation and verification for aeronautics (and space), therefore, must be developed using funding from other sources.

Integrated Design and Manufacturing Aids

The development and use of advanced, integrated tools capable of significant reductions in the elapsed time to production of aeronautics products are extremely important to the aeronautics industry. Again, while some work will be done in this area, the aeronautics community needs to motivate work in order to take advantage of the full potential available. Efforts should concentrate on standardization of interfaces and data representations (intermediate forms) so that the support industry can work on its individual specialized areas. Special attention should be paid to interfaces between groups not normally supported by the same set of tools. For example, a formal specification language and related modeling tools can be used effectively during the discussions between manufacturers and customers that lead to an agreement as to the projected capabilities of the planned product. Direct integration of the design tools with the specification language would allow straightforward traceability anytime within the implementation process. A full set of configuration management tools, as well as manufacturing and test tools integrated with the design tools, would complete the package. This integrated environment would provide the flexibility needed to utilize effectively the manufacturing facilities during dramatically varying periods of demand. Integration activities should recognize that full benefits would be gained only when the manufacturer's set of tools is integrated with those of its vendors. For example, the aeronautics industry is a small-volume market to the semiconductor industry. In order to be responsive to the requirements of the aeronautics community, the semiconductor industry will need to continue its effort to implement low-cost ways to execute low-volume production runs.

Artificial Intelligence Applications

Many new applications of artificial intelligence, or expert systems, can be envisioned within the aeronautics community. The utilization of these capabilities will be important to achieving significant reductions in the cost of implementing certain aeronautics systems. At present, the requirements of the aeronautics community do not appear to diverge from those of others currently developing artificial intelligence systems. The aeronautics community would be able to utilize ongoing developments in this area without initiating additional efforts.

Theorem proving must be developed to support the validation and verification of computer systems. This will involve specification of languages and formal development procedures. The difficulties of asynchronism (time dependencies) can not be ignored, and temporal

logic, or its specialized equivalent that can be applied to validation and verification, will be necessary. Methods of validating such models that are applicable to the actual systems (the relationship with testing) must be developed.

Report of the Panel on

Human Factors

William B. Rouse, Panel Leader
John K. Lauber, Rapporteur

HUMAN FACTORS

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HUMAN FACTORS

Introduction

Human error in the operation of complex systems is the largest single cause of incidents, accidents, and the loss of lives and dollars. Therefore, it is understandable that the focus of human factors research and engineering is on increasing our understanding of the basic mechanisms of human error and on developing techniques for reducing or eliminating the various causes of human error.

This traditional approach to human engineering, or ergonomics, a discipline born of a marriage between engineering and psychology, has in the past emphasized "knobs and dials"--fundamental issues of legibility and operability as determined by the basic operating characteristics (such as visual acuity and anthropometric dimensions) of the human being. More recently, the advent of computer technology has permitted the system designer to automate some tasks previously performed by the human, thus eliminating even the potential for human error in the performance of those tasks, and often enhancing overall system performance. However, in some cases the application of automation technology not only has resulted in the creation of entirely new opportunities for human operator error, but has reduced the performance of the complete system and increased training costs. It can be argued that experience to date with large, complex, semiautomated systems suggests that we may have reached some limits in our ability to integrate effectively complex technology and the human operator, and that we must develop better understanding and new approaches to human-machine system design. Continued emphasis on physical technology alone will not solve the improved performance and "human error" problems.

The panel believes that a new discipline is emerging which will have a profound impact on how we will design future systems. "Cognitive engineering," although not an entirely satisfactory term, reflects the essential characteristics of this new discipline; a synthesis of elements from engineering, psychology, and computer science. This is illustrated in Figure 7-1. The goal is to develop the understanding required to establish principles and practices for designing systems that make "best use" of the human, are tolerant of human error, and reduce the costs of systems and training. While from a scientific and engineering point of view, progress is being made in improving the understanding of the principles involved, from an organizational point of view, progress has been lagging in putting the principles into practice.

This report describes some of the many research issues that must be addressed if success is to be achieved in integrating the human into advanced aircraft systems that are more efficient and effective, but more complex due to the advances in and the application of electronics

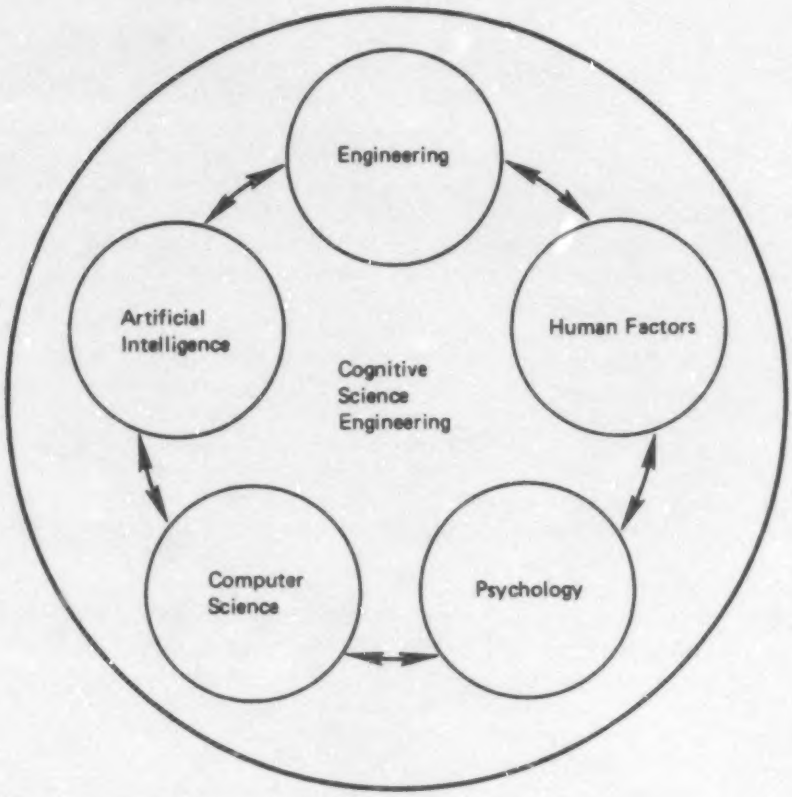

Figure 7-1 Cognitive science/engineering--integration of disciplines.

for all operational and informational functions. The panel believes that it is critical to undertake this effort if the United States is to remain a leading force in the development, manufacture, use, and export of future advanced aeronautical systems.

The principal focus of the discussion that follows is upon human factors research issues for civil transport aircraft design and operation in the year 2000 and beyond. However, most of these principles and issues are generic and apply equally to other classes of aircraft and missions, and for that matter, to any complex, man-machine system. Human factors research related to combat aircraft has been addressed in two recent reports by the National Research Council (NRC) and the U.S. Air Force that are cited in the bibliography. Thus, the panel did not consider that subject in its deliberations. The Air Force study also addressed the biomedical and physiological research aspects of crew protective systems, so this matter is not addressed.

In preparation for its study, the panel reviewed the reports noted as well as other relevant reports, including an International Air Transport Association Information Paper on "Technology Developments in the Next 10-15 Years." The panel also was apprised of a study of a National Academy of Sciences/National Research Council working group on simulation that has examined matters relating to the use of simulation to support the human factors aspects of design; research needs in the areas of performance assessment; efficient experimental and test system design; consideration of failure modes and out of tolerance conditions; and system/human performance modeling.

The selected human factors research issues addressed in detail by the panel were developed through a process of individual presentations and group discussion.

For the purposes of this study, several assumptions were made about significant technology developments expected by the year 2000. It seemed clear that a major driving force for aeronautical systems development is the revolution underway in microprocessor-based data acquisition, manipulation, and storage systems. It was assumed that the same pressures that presently are acting to force the implementation of new technology in aeronautical systems will certainly operate with undiminished and probably with increased intensity. Economic incentives, the desire for enhanced safety and reliability, and advances in the art and science of systems integration will result in increased application of automation to cockpit and ground-based systems alike.

The nature of the human operators' tasks is changed dramatically by the use of these technologies because of the great increase in the quantity and quality of real-time information available to operators on the ground and in the air. This, along with the automation of most basic flight and system control tasks, is beginning to alter significantly the role of the human operator in the system. For example, in most present-generation civil transport aircraft, a substantial portion of the pilot's task is concerned with basic flight path management and the functioning of onboard aircraft systems. In aircraft of the future, it is anticipated that virtually no manual control tasks will be performed routinely by the pilot, and that the principal activities of the crew will be to perform cognitive mission and system mangement tasks, i.e., the acquisition, processing and manipulation of symbolic information required to accomplish the mission. While the operation of present-generation aircraft already involves significant cognitive elements, these elements will become predominant in future-generation aircraft.

Because of the unique capability of humans to assimilate and process data and make decisions in the face of uncertainty and ambiguity, especially when dealing with unexpected or "non-nominal" events, human operators will continue to play a critical, central role

in aircraft operations for the foreseeable future. To achieve safe, efficient, and effective system design requires the development and application of man-machine system design techniques and criteria that will support and facilitate the human's ability to deal with unanticipated events. The research issues developed by the panel were directed at this class of design problem.

Projected Technology Developments and Their Impact on Human Operators in Aeronautical Systems

Most of the research issues discussed derive from continued evolution and application of information technology that allows the automatic collection and manipulation of external and internal information to be used to operate the aircraft at high levels of efficiency in the performance of its mission. Because of the current revolution in computer science involving the development of new ways of computing and representing information, it seems clear that essentially unlimited computational and data communications capabilities will be available for future airborne and ground-based systems. The panel believes the application of this technology will make it feasible to design aircraft and related support systems that will incorporate the design features discussed in this section.

Machine-Aided Information Acquisition, Processing, and Decision Making

The trend in the application of technology in present-generation aircraft is to relegate closed-loop control tasks at all levels to microprocessors and automated actuators, and to limit the role of the human operator to that of monitor and manager whose primary function is to intervene in the event of system failure. Available data about human performance in such systems suggests that this approach to complex human-machine system design will not be optimal. If applied fully, this design approach forces the human operator into a monitoring role for which he is not well-suited. It fails to make effective use of the human's ability to work with uncertain, incomplete, and ambiguous data--a task for which machines are not and may not become well-suited. At present, it is unclear whether future systems would be designed to augment the human operator's information acquisition and processing capabilities, or whether they would be designed to eliminate the human from the system, except to provide backup in the event of system failures. Although considerable effort has been expended in studying this question, it has been mostly of an ad hoc nature; more focused or organized effort is needed to clarify the issue.

Proper human-machine integration could provide less expensive, more reliable systems. Primary decision-making authority in these systems

will be vested in the human operator, and, in effect, the technology would be used to aid and monitor the performance of, not to supplant, the human operator. This, to a degree, is the opposite thrust of current system design philosophy.

By using such a human-centered approach in the design of future aircraft, pilots and crew, instead of simply monitoring progress would be continuously, actively involved in supervisory control employing high-technology, decision-aiding systems for critical, real-time decisions regarding the safety, tactical and strategic aspects of flight. This will entail the acquisition and processing of synthetic and symbolic information. Thus, there will be major implications for flight crew selection methods and criteria, and for the design of training, performance maintenance and equipments and programs.

Dynamic, Real-Time Adaptive Systems

Because of the inherent flexibility of microprocessor-based systems, it will be possible to design airborne and ground-based systems of the future so that they may be reconfigured in real time to meet changing system, environmental, or other requirements, including changes in the performance characteristics of the human operator due to factors such as fatigue. Currently, adjustments are made in control output gains according to mission phase (e.g., F-16). Also, it will be feasible, within limits, to tailor system characteristics according to human operator preferences and/or idiosyncrasies, or in ways that compensate for human capabilities.

Advanced Data Communications Systems

Limitations on the availability, quality, and timeliness of information to the human operator can be responsible for serious operational and safety problems in aviation systems. For example, several accidents involving encounters with wind shear and a recent runway collision appear to be, in large part, attributable to poor information transfer. Great advances are expected in sensor technology and in our ability to transmit, store, and present environmental and operational information to the crew.

Advanced System and Human Performance Measurement Technology

Advances are expected in methods and techniques for the measurement, analysis, and assessment of system and human operator performance. This technology will have a significant impact on human operator selection and training, system design, and real-time operations. For example, nonintrusive monitoring of pilot

physiological functioning may permit onboard assessment of pilot fatigue, arousal level, and mental alertness.

Onboard, On-Line Human Operator Training Systems

The application of microprocessor-based technology and some of the derivative technologies discussed above will make it possible for system designers to incorporate onboard, on-line operator training, and performance checking systems. The development of such "embedded" training systems requires that human operator training requirements be considered at the earliest stages of system design in order to have a significant impact on the economics of personnel training program development.

Advanced Flight-Control Systems Technology

Projected developments in flight-control systems technology could make obsolete the requirement for training and maintaining basic attitude and power flight control skills in civil transport aircraft operations. However, this is a controversial issue. The development of "intelligent" flight control systems has major implications for basic control/display system design (if the pilot is not to be required for flight control) and for crew selection and training.

Although there will be many other significant aeronautical technology developments by the year 2000, those identified above were selected for consideration because they have far-reaching implications for the direction of human factors research and technology development.

Human Factors Research Issues in Support of Technology Development for the Year 2000

Based on the above, four major categories of aeronautical human factors research were identified for further discussion. They relate to human abilities, computer interfaces, design processes, and operations and productivity.

Characterizing and Assessing Human Abilities

Human Performance Modeling The need for human performance models stems from the need for predictive methods for evaluating total system performance. These models will represent human performance via mathematical or perhaps symbolic formulations or computer simulations, which are less costly and provide more timely information than empirical methods using simulators or mockups with human operators.

Several different models, the specific uses, and needed research are addressed here.

A primary need is for models of human information processing, i.e., theoretical descriptions of how the human acquires, manipulates, and transforms information. Current models, based on time line analysis, can predict times for elementary movements, reactions, eye movements, and memory decay. These models are generally descriptive rather than predictive. However, one group of researchers recently has developed an explicit, limited-activity-domain predictive model. Such a model provides guidance in understanding relatively simple human-computer interaction tasks (e.g., text editing), but is not sufficiently well developed to give substantial aid in designing the human-aircraft interface.

A second class of model is the human-machine system model. The basic assumption for these models is that well-motivated, well-trained humans perform optimally within the limits of human information processing capabilities and the task environment. One notable success in the development of such a model is the optimal control model. This model provides a good description of the human as a manual controller in complex aircraft. However, in present generation transport aircraft, humans do little manual control, and they may be required under nominal operating conditions to do even less, if any at all, in aircraft of the future. Although the task environment will change, some of the constructs underlying models such as the optimal control model are likely to be applicable.

The principal direction of future research and technology development should be to produce more detailed models of humans performing complex information processing and operating tasks such as those required by flight crews for flight and operational safety and performance optimization. Future modeling efforts should be directed toward the development of models that describe human monitoring and intermittent and supervisory control of automated systems, fault diagnosis, and responses for complex system operation, the primary tasks of humans in future aviation systems.

Another need is for a better understanding of mental models, i.e., the human's internal representation of the structure and functioning of a complex system. Mental models provide the basis for the human operator's decisions and actions. They include refining the model to represent the process of learning to use and operate systems. In effect, "covert" behavioral processes operating through the human's mental model provide the foundation for developing "overt" human and human-system performance models. Having a correct mental model of a system is particularly important for diagnosing system faults or controlling the system under unusual circumstances and deciding on appropriate corrective action. An understanding of mental models is useful for designing training systems to teach human operators to

develop accurate mental pictures of systems. This is especially important because often in practice faulty mental models are the rule, not the exception.

The final topics are expertise, skill retention, and training. Although expertise can be recognized, there is little understanding of exactly what it is or how to produce it (except for the obvious, expensive method of training persons of high ability). Although we can define the content of expert knowledge in limited domains, we do not understand the internal structuring of knowledge, i.e., the what and how of expertise.

Similarly, skill retention is a poorly understood phenomenon. Because of the occasional requirement for a human to perform functions normally performed by the machine, it is important to understand the factors that affect the retention of skills during periods of disuse.

The topics of learning, skill retention, and expertise are related. The objective of education and training is to impart expertise. Ironically and unfortunately, we do understand what expertise is in certain limited domains, but we do not have a general understanding of what it is or how it relates to skill and the retention of skill. There is a risk that the currently popular but limited notion of "expert systems" will be inappropriately relied on and will inhibit the research and technology development important to the growth in understanding of this important relationship.

In summary, one of the major thrusts of human factors research should be in the development of techniques and concepts that will model the performance of the human operator in complex, highly automated systems. Based on past experience, a major problem will be the integration of such models into the design process and getting designers to use and help develop the model.

Human and System Performance Measurement Methodology

Measurement is essential to provide information for design, management, and training for operation of aircraft. Measurement issues around the year 2000 will be extensions of current ones, taking into account new technology, the changed role of crews, aircraft operating procedures, and changes in the national airspace system. Future methodological measurement issues center on criteria development and validation, i.e., what are the important performance indices including the minimum acceptable levels of performance. Another increasingly important methodological issue is how to measure performance relating to understanding and response.

A third important measurement problem is currently the subject of intensive investigation, but is likely to continue to be an important

issue: the development of reliable, quantitative indices of mental workload. One of the major consequences of automation is to change the character of pilot's workload from physical to mental. Moreover, not all kinds of mental activity have equal effects on workload. It is well established that, in some circumstances, simultaneous tasks can compete for the same cognitive resources, creating a high mental workload. But, in other circumstances, tasks can draw on human resources with very little additional workload imposed beyond that of the task alone. The ability to measure not only static physical levels of workload, but changes in mental workload over time is a critical matter for both design and operational analyses.

Adaptive measurement of covert performance, information processing, and the related mental workload likely will involve tapping physiological processes such as electrical signals (electroencephalograms [EEG], evoked response potentials, etc.), autonomic nervous system effects (heart rate, respiration, sweating), and muscle tension. Current research on physiological indices of cognitive activities is promising but rudimentary.

The ability to synthesize neurological and physiological indices into measures of specific cognitive states is certain to be a dominant research concern in support of technology development for the year 2000. The ability to reliably measure even a few key cognitive functions through neurological and other physiological means implies the possibility of extending the human-system interface to include direct (biocybernetic) control. Realization of biocybernetic control should provide a means for allowing dynamic change in the allocation of tasks between the human pilot and automated systems (discussed in the next subsection). Also, it could provide maintenance of optimal pilot workload as well as monitoring of the human to catch lapses of attention, mistakes, and neglected procedural responses, and could provide attentional and cognitive tuning of the human operator.

Biocybernetic sensing and communication could permit computer monitoring of a pilot's (crew) or air traffic controller's physiological responses such as blood pressure, heart rate, and EEG. These would permit predictions of crew alertness and readiness for response and of their psychological health when compared to a template for the same tasks under similar operating conditions. The questions of how to identify these physiological signals in the presence of noise, how to translate these signals and develop meaningful diagnostic algorithms that minimize false alarms, and how to reliably predict the pilot's physiological health and level of alertness will require considerable research.

A further important measurement problem that is certain to continue is the development of predictive indices of performance for selection of pilots, crew, and ground operators. Current paper and pencil tests are poor predictors of crew and operator ability. Performance-based

testing using simulators and other measurement devices is in its infancy, but should be well developed over the next 15 years. Defining abilities, whether latent or learned, and finding simple, reliable, and valid indices of these abilities should be of prominent concern.

Human-Computer Interfaces

Adaptive Systems An adaptive system has the ability to change its parameters, structure, and priorities as a function of feedback from the system and the operating environment. Since the priorities of an adaptive system can change in subtle ways throughout a mission, key research issues center around how to allocate tasks, in a dynamic manner, between the human crew and the "electronic crew," and how to inform the human operator of the present status of the adaptive system. Although some guidelines for task allocation are available (generally, computers are good at handling large amounts of data, humans are not; humans are good at ambiguous pattern recognition, computers are not), the guidelines relate relatively to static situations. The research issues of concern involve dynamic situations that require the determination of a method for assessing the overall performance of human and machine at any instant in time; the determination of upper and lower bounds in the information processing channels for both components; the determination of when to reallocate tasks as a function of degradation or overload of either component; the determination of the method of communication, especially from the machine to the human, when the former sheds or assumes tasks; the determination of priority schemes for allowing the human to override some or all of the machine's allocated task decisions; and the determination of whether a third party (ground-based, human, and/or computer) is needed to arbitrate task allocation disputes.

A primary means of communication between the human and electronic crew members will be through integrated electronic displays, e.g., electro-optical, full-color displays, and voice input and output technology. Relative to adaptive systems, research issues in integrated controls and displays include methods and criteria for determining and displaying instantaneous system configuration; determination of which particular display modes, e.g., mix of synthetic representational, symbolic, and "raw" data, are appropriate in any given set of circumstances; and methods for representing specialized information, e.g., spatial information.

Such basic control/display research and technology development may result in the achievement of a true symbiotic relationship, a full-fledged partnership, between the pilot and the avionics systems. Hopefully, this will reduce the tremendous information load imposed on the operator resulting from displaying very large amounts of complex

information using symbols and signals that are not in a "natural" language.

Human-Computer Dialogue The safety and flow of aircraft in the national airspace system depends on efficient, timely, and error free information exchange among crew members, ground personnel, air traffic control, and onboard computers. Future human-computer communication links will include voice recognition/computer translation (VRCT) and physiologically based human-computer communication.

One of the major research issues in this area is the development of natural language for human-computer dialogue. Because of the use of idiomatic expressions unique to aircraft operations, it will be an essential requirement for using VRCT to develop natural language conventions whose meanings are universally and flawlessly understood by air and ground personnel. The basic research to be addressed relates to the development of techniques for machine translation of verbal information as a function of mission and flight phase, accommodating sequential dependencies and emergency situations.

VRCT offers the potential of dual modality (auditory and visual) presentation and retrieval of air-ground communications. A major research concern is with the determination of the trade-off between added cockpit (or air traffic controller) visual workload and improved message exchange through use of dual modality communication links.

Other design questions need to be addressed also. They include the basic issues of optimum format, organization, and presentation of dual modality information with integral prompting and aiding to aircrew and ground personnel.

Regarding situation awareness, authority, and human intervention: as aircraft systems increasingly become automated, it may be difficult for the human to maintain awareness of the total operational situation. Of concern is the extent to which humans must be apprised of the processes whereby control is being achieved in order to assure that the human can intervene if necessary.

A related issue concerns the strategy whereby the human should intervene and recover when automation fails or a situation is encountered for which automation was not designed. One question relates to how the human determines that intervention is necessary and another question is how the human can take over, perhaps in midtask, and deal with the problem. Answers to these questions may have important implications for design, aiding, and training.

The problems of maintaining awareness, intervention, and recovery become particularly difficult for unanticipated, rare events. The question of how the human can be prepared for and aided in dealing with the unknown is crucial. The possibility of such situations will

be one of the primary reasons for retaining humans in aircraft of the future. The notion of supporting a human to perform an undefined or ill-defined task may require that design, training methods, and aiding schemes be rethought entirely.

The use of computer-aided systems and "electronic crewmembers" on the flight deck may cause changes in the complex social structures among crew members and other humans in the system. Since these relationships can affect communication and team or group performance, it is essential that systematic study of the social and organizational climate in the aviation system of the future be undertaken.

A final issue relates to who (human or computer) will have final authority and responsibility. While it is easy to say that the human will fill this role, trends in automation (i.e., expert systems) may lead, in the longer term, to a de facto allocation of this role to the computer. This is a volatile issue that has to be addressed directly to produce guiding principles for future systems.

Design Process Enhancement

Results from research and technology developments related to the above issues must be translated into practical design and application processes. The following commentary discusses several of the issues addressed above, as well as some additional needs as they impact design and development. The emphasis is both on application of new data and the implementation of improved procedures and practices.

Crew Station Design The process used for crew station design needs considerable augmentation to better deal with new automation and control/display concepts. The following areas should be considered:

- Engineering simulation, computer simulation, and human performance modeling and measurement:
  - -- One important tool for crew station design is a high-fidelity simulator available in the early conceptual phases that can be modified to reflect the evolving system. Such a simulator should reflect the air traffic control, communications, and ground-based environments expected in the future. The techniques used should reflect the newer automation concepts and an appropriate performance measurement system should be incorporated for handling normal and degraded modes of operation. The simulator also can be a valuable adjunct for the introduction of new crew station design concepts.

-- Criteria must be derived for future missions to develop performance measurement requirements. These must be validated and implemented for use in engineering simulators and development aircraft. Performance data should be available on a near-real-time basis to be useful for design, and ultimately, for selection and training.

-- The application of high-fidelity simulation in the early design process must be coordinated and integrated carefully with the application of human and system performance modeling and computer simulation techniques. Much of the preliminary evaluation of design concepts should be done analytically and through the use of these techniques, reserving the application of costly full-mission simulation for otherwise intractable problems and issues.

o System logic design criteria: Design criteria and methods should be derived for use in designing the logic of complex man-machine systems. Factors such as dynamic function allocation, decision making, display format, and control mode complexity must be considered. Present human factors design criteria are not suitable for such use, yet the system logic is the key entry point for human factors inputs to automated systems.

o Cost/simplicity design criteria: Computer and software developments have the potential for effecting major increases in the cost and complexity of the crew station and impacting life cycle costs through training demands. Deliberate and continuing design surveillance is necessary to keep these advances at an appropriate level. Cost-related design criteria and data bases need to be developed that can be applied throughout design.

o Cockpit/trainer system integration: The crew station and training system should continue to be designed in parallel. This permits the better use of training requirements as a design criterion. Engineering simulation and human performance modeling have the potential to serve as a rich source of data for training system design, as well as to permit early consideration of embedded training concepts. The implementation of this parallel development for the future requires enhancements to existing design approaches and methods. It has a large potential for cost avoidance, if future system support and training costs are minimized.

Computer-Aided Human Factors Design While many concepts and large amounts of data have been generated by the human factors research community, this material tends not to be used or useful during design. The information is not in a form for ready application. There is a need to use a computer data base approach that can be integrated with the design process and assist designers in asking and answering human factors questions at appropriate points in the design

process. Such a system could expedite the transfer of human factors technology to products. In concert with such action is the need to add a human factors subsystem to computer-aided design programs, since future design efforts will minimize the use of drawings and physical design aids.

Function Allocation Methods Function allocation is a classical human factors problem (i.e., what should humans do and what should machines do?). While a variety of approaches to allocation have been developed, these approaches are insufficient when the machines of interest are intelligent computers whose adaptability and abilities overlap those of humans. Further, air-to-ground data links complicate the issue since the allocation of function between air and ground may no longer be based on the "natural" division of functions. In general, the functional allocation must consider a greater number of interactions among system components than previously identified and the impact of on-line, dynamic function allocation.

Cockpit Standardization Commercial airlines view standard cockpit configurations as highly desirable to permit greater flexibility in assignment of crew members and to reduce training requirements and costs. The B-767 and B-757 have virtually identical cockpits, and the obvious advantage enjoyed is likely to provide the impetus for standardization over greater ranges of aircraft size and possibly between aircraft of different manufacture.

Different aircraft, however, have different flight characteristics. While it may be relatively easy to standardize procedures, specific differences in performance and handling qualities require different flight-control and operational techniques.

Automation and computer-based control and display systems offer the opportunity for nominally removing aircraft differences where crews are concerned. Current practice is to set instrument controls to values having a generic functional meaning such as V1, V2, Vr, etc. Given automatic computation of these data, displays to the pilot need not indicate absolute physical values, but rather, operationally relevant symbolic values. For example, an airspeed display may similarly show V1, V2, Vr with some allowable range limits and no numerical values at all. Other instruments could display operationally meaningful symbols such as cruise speed, maximum Mach number, fuel flow in terms of "low, normal, or high" rather than in physical units. Similarly, flight-control characteristics can be made the same regardless of aircraft size, and by mission phase as in the F-16. This approach to functional standardization of cockpits would be a radical departure from present philosophy and entirely feasible for aircraft of the future.

Logistics and Operational Productivity

Selection The air crews that will operate aircraft developed for the year 2000 probably will be substantially different from current air crews. The tasks related to aircraft safety and efficient operation will be concerned more with resource management and decision making (involving different cognitive components) rather than the direct system operation that exists today. Research for the year 2000 system needs to focus on developing task and skill taxonomy and the supporting behavioral understanding that will be required to make use of the greater system capabilities that will be available. Issues involved should include determining the abilities needed, developing criteria by which these abilities may be measured, and developing tests to predict these abilities.

Also, it should be recognized that motivational variables that can affect both the demographics of the available manpower and the performance of air crew duties may change substantially by the year 2000.

Design of Training Systems Training is one of the trade-offs in the system design process; training systems have to be developed to support the final design. Several areas of research should be supported to permit the development of effective training systems at reasonable costs. Research needs to concentrate on a hierarchy of training methods and media (including devices) to make the most effective use of resources. Current full-mission simulation is very costly. Costs are driven by visual and motion systems and by computer hardware and software. Research for the year 2000 should focus on advancements in areas such as embedded training, low-cost simulation devices, interactive video disk technology, computer-based training, and methods to determine the lowest cost training consistent with performance effectiveness goals.

Maintenance Support Fundamental changes in the ways maintenance is performed can be expected with future generation aircraft. Because these changes will affect the very nature of the maintenance task, selection, training, and support/aiding of maintenance technicians could become important research and development issues. Guidelines and principles for designing common technical data bases and technical orders for troubleshooting and repair and for maintenance technician training could be a research need. It is currently very expensive to develop and maintain this training and technical data system. Methods for the development of cost-effective application of technology such as video disks or computer graphics for the maintenance and use of technical data bases are significant research issues. The use of low-cost, helmet mounted [telemetered] display technology for use by maintenance technicians should be researched.

Aircraft Ground-Handling/Servicing With the predicted increase of traffic loads for major airports for the year 2000, a capacity/limitation problem may be the efficient ground movement and handling of aircraft. Research is needed on ground communication techniques and procedures, ground vectoring under zero visibility conditions, and improving servicing techniques.

Cabin Crew and Passenger Handling Cabin crew and passengers are confronted with a wide variety of sizes and operating instructions for emergency exits and escape routes. As large-aircraft design matures, it is desirable that standardization and optimization of exit operation be achieved in terms of the ergonomics of operation (handle location and operating force) and the "naturalness" of the actions required to open the door and exit the aircraft (one intuitively pushes a handle outward to go out, for example), and marking of escape routes so they can be determined in a dark, smoke-filled environment wherein overhead markings may be invisible to a crawling escapee.

Organizational Productivity Though not a direct technology issue, productivity is an important concern. The United States must maintain a position of leadership in aircraft development, manufacture, and operations. Technological advances alone may not achieve this goal. Productivity improvements need to be applied to the total spectrum of aviation including design, development, and testing; manufacturing and quality assurance; and operations and logistics. The goal is to produce better products at lower costs. Present approaches have not been very successful because they have been piecemeal, lacking the structure and technique needed to effect broad change and savings.

Technologies and processes must be developed and applied to effect these improvements. They have their basis in the behavioral sciences (industrial and organizational psychology) and in the engineering and computer sciences. Some elements of this technology include computer-aided design robotics, improved fabrication techniques, advanced maintenance concepts, and appropriate consideration of manpower/skills trade-offs during design.

Report of the Panel on

Systems Integration

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Dominic J. Maglieri, Rapporteur

SYSTEMS INTEGRATION

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SYSTEMS INTEGRATION

Introduction

Projections of technological advances to the year 2000 have suggested a number of possible conceptual types of air vehicles. For convenience, these have been grouped according to speed, increasing from below Mach 1 (including hovering flight) through various Mach ranges to orbital flight. The potential performance capabilities that could be realized for each of these types of aircraft provide exciting prospects for the years beyond 2000. It is clear that the greater design flexibilities provided by the projected technology advances will permit significant improvements in performance, economy, and safety and allow the design and development of aircraft systems that current technology will not support.

In the following sections, each vehicle type is discussed, noting design features and significant advances. Where related aircraft exist, the significant economic and performance factors are compared. In addition, for each concept, the technology developments considered essential for the advanced concept are identified. The types of aircraft described are examples of what advances in the technology projected for the year 2000 could provide. They are by no means all that would be possible.

The panel's views on the current state of knowledge of systems integration as a discipline and the need for advancement in this area are presented in the concluding section of this report.

Vehicle Types--Hover to Mach 0.8

The first group of vehicle types, speed range from hover to Mach 0.8, is represented by rotorcraft and vertical takeoff and landing (VTOL) vehicles.

Rotorcraft/Vertical Takeoff and Landing Aircraft

The present fleet of rotorcraft includes both civil and military types. Many of the U.S. civil rotorcraft are based on military systems which are, in general, technologically the more advanced. Military systems include troop transport (CH-46 and CH-47), medical evacuation (UH-1B), forward battlefield preparation (CH-64 and UH-1B), and attack (AH-1 and AH-64). These classes of military rotorcraft have dominated the world market but may not continue to do so. In the civil market, foreign competitors have made significant inroads. The civilian uses of rotorcraft range from police work and ambulance service to commuter transportation to operational support of offshore oil fields.

The potential capability improvements for the three primary classes of rotorcraft are:

- o Attack
  - -- worldwide self-deployment
  - -- all-weather/night/nap-of-the-earth operation
  - -- extreme agility/direct engagement
  - -- two to three times current speed and range
  - -- up to three fold improvement in flight safety
  - -- precision controllability in terminal operations;

- o Utility
  - -- 40-ton payload
  - -- double current range
  - -- 30 percent reduction in noise and vibration
  - -- up to three fold improvement in flight safety
  - -- precision controllability in terminal operations; and

- o Civil
  - -- up to twice current speed and range
  - -- up to twice current payload
  - -- 70 percent reduction in noise and vibration
  - -- up to three fold improvement in flight safety
  - -- precision controllability in terminal all-weather operations.

The advanced rotorcraft would include conventional helicopters, large transport and heavy-lift helicopters, special designs, i.e., advanced blade and tilt rotor and small, low-cost helicopters.

Future (or year 2000) helicopters would be characterized by improvements in speed and range, reduced operating costs, and reliable performance under all weather and environmental conditions. This advanced helicopter would have a 30 percent lower airframe weight and operate with a 40 percent reduction in fuel. The cruise speed would range to 500 knots. These advances would result in a 70 percent productivity improvement over present-day helicopters. This helicopter also would be characterized as being very quiet (acceptable to the urban and residential environment) with a jet-smooth ride quality and a cabin internal noise environment equal to today's jet transport.

Large civil helicopter transports may emerge to serve the short-haul market in Europe and the United States. For example, a large transport helicopter (approximately 200 passengers) might be conceived that, under certain economic conditions, would complement fixed-wing short-haul transports for stage lengths from 50 to 300 nautical miles at comparable costs with today's short-haul transports. Additional opportunities for large, heavy-lift vehicles (40-ton payloads) likely would emerge as a natural outcome of the growing needs of the cargo, construction, logging, and resource exploration industries.

Finally, small, low-cost helicopters will appear for personal, recreational, and training use. Safety is a critical issue.

Specialized rotorcraft configurations would enable much higher speeds than conventional helicopters for certain missions, creating new aircraft uses, and displacing some current aircraft. These advanced rotorcraft configurations would be characterized by high-speed performance. They include an advancing blade compound helicopter, tilt rotor, folding tilt rotor, and stopped rotor aircraft.

An advancing blade compound helicopter (based on the XH-59A technology) would provide speed increases of 50 knots, be very agile, and enable landing in more compact spaces under severe weather conditions, while retaining the stationary hover efficiency of the conventional helicopter.

Tilt rotor aircraft would double the practical operating range of conventional helicopters while flying twice as many passenger miles per gallon of fuel as today's helicopters--at twice today's speed. An advanced tilt rotor would enable 400-knot cruise speeds.

Sometime after the year 2000, other new rotorcraft would have VTOL capability with high subsonic speeds (up to Mach 0.8) and ranges comparable with today's short-haul transport jets. The folded tilt rotor could be used for distances up to 1,000 miles where VTOL and STOVL is required. Occasional hover and low-speed tasks also would be performed.

Another rotorcraft configuration having potential as a high-speed vehicle is the stopped rotor, such as the X-wing. The X-wing rotates and functions much like a helicopter rotor for vertical takeoff. Once the aircraft is airborne and reaches a certain speed, the X-wing locks in place for forward flight. This vehicle is expected to have a cruise speed potential to 550 miles per hour and range to 1,000 statute miles, and high-altitude capability. This vehicle would be suited for missions that require rapid, long-range transport and hover at the destination.

Several key technologies underlie development of the capabilities envisioned for advanced rotorcraft vehicles. The most challenging relate to the development and verification of rotor systems. All of the advanced rotor concepts being pursued would require extensive use of digital control systems. In addition, there exists a real need for bearingless or air-bearing rotors. This, coupled with rotor boundary layer control for high performance, brings to focus a new and extremely complex, integrated discipline research need, aero-servo-pneumatic-elasticity, i.e., the interaction of aeroelastic, servoelastic, and pneumatics for rotor controllability and high performance.

Another challenge for efficient and effective rotorcraft is in the area of man-machine interfaces. Control systems integration and advanced displays can reduce substantially the pilot workload, thus improving both safety and utility. Precision controllability in the terminal area as well as in maneuvering flight would allow a much expanded role for rotorcraft in both military and civilian application.

Improvements in rotor aerodynamics would be required for pushing rotorcraft to higher cruise speeds. Improvements also would be required in the classical configuration aerodynamics and component interaction to reduce the basic vehicle drag levels relative to those of current configurations.

The development and use of lightweight, high-strength materials/structures would be required for effective development of advanced rotors, structures, and controls.

Continued development of power transmission systems to reduce both the noise and vibration should be considered as a key technology for future rotorcraft.

Vehicle Types--Speeds up to Mach 1

The second group of future aircraft types, having speeds up to Mach 1, are represented by the long haul airlifter, advanced assault transport, extremely high-altitude aircraft, and subsonic transport.

Long-Haul Airlifters

The current equivalent to the long-haul airlifter is the C-5A/C-5B (or the freighter versions of B-747). Based on projected technology developments in structures (composites and advanced metals), aerodynamics (laminar flow control on wings, empennage, and turbulent drag reduction devices on the fuselage), and propulsion (advanced high bypass turbofans or propfan systems), the long-haul airlifter of the future would have capabilities that far exceed those of its present-day equivalent. For example, the new airlifter would have a range of 10,000 miles and range-payload trade-off capability two to three times that of the C-5A, while having a takeoff weight only about one-third more than the current aircraft.

There are many technologies that will have to be advanced to support the design of an efficient long haul airlifter. Of these, the following are considered to be the most important.

- Advanced laminar flow control (natural, hybrid, or fully active) would eliminate 80 percent of wing and empennage viscous drag reduction with minimum impact on cost and complexity. Reduction of turbulence on the fuselage would allow related drag reductions of 25 to 30 percent.

- Propfan propulsion systems would offer 40 percent savings in block fuel at M = 0.8 compared to current turbofan engines. The concept of counter-rotating propfans is a particularly intriguing concept.

- High-strain composites for use in primary structural applications (wings, fuselage sections) under carefully orchestrated structural optimizations could offer as much as a 30 to 40 percent reduction in empty weight compared to the aluminum structure of the C-5A. One of the most efficient configurations is the span-loader (flying wing) where the payload helps to alleviate structural loads. Multiple fuselage configurations might prove to be beneficial in reducing wing weight and (where large internal volume is not required, such as in passenger configurations) without drag penalties.

Advanced Assault Transports

There is no current aircraft having capabilities equivalent to those envisioned for an advanced assault transport. Current military transports are designed to deliver troops and materiel in a low-threat environment with very little consideration given to aircraft survivability.

The future tactical assault transport could make use of terrain following/terrain avoidance/threat avoidance and survivability enhancement features to penetrate up to about 400 miles beyond the forward edge of the battle area to deliver troops and materiel quickly and effectively.

The advanced assault transport would be capable of deployment and autonomous operations on a 24-hour per day basis and under virtually all weather conditions. Short takeoff and vertical landing (STOVL) capability should be available by application of advanced propulsion, control, structure, and aerodynamic technologies. The advanced assault transport must have a high level of battle damage tolerance and field repairability to achieve high sortie rates and readiness levels.

The key technologies considered essential to achieve the capabilities of the advanced assault transport concept are described below.

- Advanced propulsion systems that provide the penetration and STOVL capability are required. Survivability enhancement features also would be incorporated in the propulsion system, similar to the manner in which they are integrated within the airframe.

- Structures are required that are lightweight but capable of withstanding the severe loadings resulting from penetration at low altitudes over uneven terrain. Extensive use of high-strain composites and high-strength/low-density materials will be

necessary. Active load alleviation and ride control systems are examples of possible ways to reduce structural stress and strain and improve ride quality.

- Other technology developments include
  - -- turbulent drag reduction devices on the fuselage/afterbody and wings for improved performance;
  - -- advanced controls and displays for work reduction in a very high workload environment; and
  - -- supercritical/advanced airfoils for low-profile drag.

Extremely High Altitude Aircraft

No current aircraft has the capabilities equivalent to those envisioned for the extremely high altitude vehicle concept. Earth satellites are now capable of performing some aspects of the missions envisioned under this concept, but it is recognized that satellites might not be available in times of crisis.

Projections of technology advances in lightweight structures for application in satellites and spacecraft, coupled with some revolutionary propulsion concepts, make it possible to conceive of an extremely high altitude (above 80,000 feet), low-speed (less than 300 knots) unmanned aircraft for missions involving reconnaissance, communication, and navigation. Its flight time would be seven days or more if special propulsion systems (solar, laser, electric) are developed. Launch modes have not been defined at this point; however, a suitable flight management system will need to be developed to overcome difficulties anticipated in the flight regime during transition from low-altitude to extremely high altitude flight.

Key areas of technology needed to support the concept of an extremely high altitude aircraft are a long endurance/lightweight propulsion system and ultra-lightweight structures.

In addition, other technology developments required include

- high-altitude/low-Reynolds-number airfoils with extremely high lift-to-drag ratio (over 50 to 1); and
- lightweight flight-control/guidance/navigation systems and sensors.

Subsonic Transports

A number of subsonic transports exist today that differ from one another only in size, number of engines, and range/payload capability. These range from the large passenger transport with four

engines, a payload of 150,000 to 200,000 pounds, and a range of 5,000 to 6,000 miles to the small business jet transport, with one, two, or three engines and the ability to carry from 5 to 10 passengers over a range of 2,000 to 3,000 miles. Within the same class, these aircraft employ the same basic elements of design technology, i.e., similar structural elements, electronics, hydraulics, and air pressure systems and provide relatively the same degree of navigation and communication capability and the same comfort level to the occupants.

Improved operating efficiency and increased safety are likely to be the dominant future target capabilities for subsonic transports. In the next 20 years, technological developments are projected to provide a 20 to 30 percent improvement in overall operating efficiency. With regard to aircraft safety, in the past, much safety degradation has come from improper operation of the vehicle (pilot error) and relatively little from failures due to aircraft basic design. By the year 2000, the capability should exist to overcome personnel error by better understanding of human factors coupled with computer development directed toward the automatic prediction of potential problems giving appropriate corrective action before a critical condition is reached.

Key technology efforts needed to support the advanced subsonic transport concept include

- a more intense, influential role in design of aircraft by human factors engineers would involve principally the flight crew area; human factors aspects also would be given increased consideration in the handling, testing, and maintenance of aircraft and its systems;

- advancements in propulsion efficiency would improve reliability and safety, but the need to explore the efficiency aspect needs to continue with increased emphasis. Research and development is needed to improve the life and reliability of bearings and reduce blade erosion from ingestion of foreign matter. Other areas needing propulsion technology development include improved instrumentation and methods for determining the state and efficiency of the rotating machinery and techniques for applying turbine power to propeller propulsion;

- the development and application of new materials with emphasis on operational inspection and repair criteria, as well as emphasis on safety is needed. Regarding safety, there is a need for a nonflammable, nontoxic cabin lining material; and

- systems integration developments aimed at simpler operational and cost-reduction techniques are needed including additional effort to develop computer software that can be readily modified. Design techniques for the year 2000, compared to those of today, would

have the capability to provide far more accurate predictions of life limits for structures.

Vehicle Types--Mach Range 2 to 4

The vehicle types selected in the Mach number range 2 to 4 include an advanced fighter aircraft, a supersonic transport, and a supersonic short takeoff-vertical landing (STOVL) attack aircraft.

Advanced Fighter Aircraft

No current aircraft has capabilities equivalent to those envisioned for the advanced fighter aircraft concept. The present SR-71 aircraft can cruise at a Mach number approaching that of the supersonic (M = 3.5) advanced fighter, but it has limited maneuverability and a small payload because of its heavy titanium structure needed for high-temperature operation. The new aircraft would use improved heat-resistant structural materials that would be available by 2000 to reduce weight and improve performance.

The next generation of advanced tactical fighter aircraft now beginning concept definition will be based on technologies that will be available in the late 1980s. This level of technology will support a system concept having a sustained supersonic cruise and maneuver capability in the Mach 2.0 to 2.5 regime, a significant reduction in detectability relative to present-day F-15/F-16 aircraft, and short takeoff and landing capability (about 1,500 feet). In addition, it will have substantial supersonic range capability. However, further significant advances are possible with technology projections.

Considering maximum utilization of projected technology advances through the year 2000, a more advanced fighter aircraft system can be conceived having most of the following characteristics (the actual "blend" will depend on mission requirements, design trades, and life cycle cost factors):

- o supersonic cruise and maneuver capability at a Mach number of about 3.5, based on projected advances in three pacing technologies (propulsion, structures, and aerodynamics);
- o operational altitude in excess of 70,000 feet;
- o maneuver capability at the cruise Mach number in excess of 2 gs; dropping to slightly lower altitudes (55,000 to 60,000 feet), even more maneuverability would be available at high Mach numbers;
- o a "zoom climb" capability to over 100,000 feet for defensive purposes;

- high cruise efficiency and increased range; it could be feasible to fly three times farther on a given amount of fuel at Mach 3.5 than an F-15 flying at Mach 2;

- a potential radius of action of over 1,000 miles with a disposable payload of 2,000 to 5,000 pounds in a package that has "acceptable" weight and cost;

- potential for supersonic weapons carriage and delivery methods to support advanced combat mode;

- able to launch long-range advanced hypersonic air-to-air or air-to-ground missiles without losing speed or altitude, and while maneuvering to its maximum capability;

- equipped with a short-range (less than 10 miles) laser weapon or advanced guns with integrated fire-control/flight-control systems;

- use of artificial intelligence via onboard computers and sensors to provide the advanced fighter aircraft crew with a total "situation awareness" of threats, targets, and battle management information;

- have a low level of detectability to the opponent's sensors;

- have a high degree of operational flexibility: for example, relatively short takeoff and landing (STOL) capability; ability to operate on runways less than 2,000 to 3,000 feet in length, 24 hours per day, and in virtually any weather condition; and ability to maneuver at very high rates, beyond maximum lift, with no chance of spin or other adverse attitudes (i.e., maneuver with reckless abandon within limits);

- an anticipated 10 percent reduction in life cycle cost and a reduction of at least 50 percent in maintenance hours per flight hour relative to today's fighters; and

- greatly enhanced reliability, availability, and sortie generation through use of fault-tolerant/reliable/reconfigurable subsystems at all levels (propulsion, flight control, weapons, avionics, etc.).

The key technologies considered essential for the realization of these classes of performance for advanced fighter aircraft are discussed here.

The propulsion system will have to sustain high temperatures and pressures throughout the compressor, combustor, and turbine. The engine might be a compound ramjet/turbine or some type of variable cycle engine. Turbine inlet temperatures in excess of 3000°F can be anticipated. Aircraft external surface temperatures up to 1000°F (slightly higher than SR-71) can be expected. Critical hot spot areas

would be leading edges, inlets, and nozzles. Advanced metallics (powder-metal and advanced ingot alloys) as well as advanced composites (including metal matrix composites) will need to be developed for these applications. A high-temperature thin skin (titanium or other high-temperature alloy) or possibly a thin insulation blanket might be considered so that lightweight high strength-to-density ratio materials could be used for most of the internal structure.

Advanced blended-body aerodynamics will be needed to achieve high lift-to-drag ratios (say, over 8 at Mach 3) and improved vortex management techniques are expected to make maneuverability efficient at all speeds. High-angle-of-attack control systems with special control devices must be developed to assure controllable operation throughout the flight envelope.

Supersonic Transport

The only supersonic transport (SST) operational today is the Concorde, a four-engined afterburning turbojet airplane having a gross weight of about 400,000 pounds and a capability of carrying 100 passengers across the Atlantic at about twice the speed of sound. Studies in the United States indicate that to be feasible economically, future Supersonic Transports should have capabilities greater than those of the Concorde in payload, range, and speed; it should be able to meet every legal requirement (e.g., noise, pollution) and be competitive with subsonic airplanes in terms of airplane cost and fare structure.

Technology advances applicable to the SST's design since the Concorde have been significant. It has been estimated, for example, that these improvements would allow a Mach 2.7 vehicle to carry a payload of 290 passengers a range of 4,500 nautical miles at a gross weight of 640,000 pounds. With further developments in technology identified for the year 2000, additional performance, cost, and/or efficiency improvements would be possible. For example, it is anticipated that it would be possible to accomplish the 4,500 nautical miles mission at a much lower gross weight.

Key technology areas to support an advanced supersonic transport include a higher overall efficiency propulsion system (e.g., an increase of 500°F in turbine temperature would provide significant improvements in engine cycle efficiency as well as in engine thrust-to-weight ratio); lightweight, temperature resistant, low-cost structures (e.g., thermoplastic composites or new aluminum alloys); low-cost sandwich construction techniques to enable the fuel to be used as a heatsink; short diffuser inlets; and supersonic laminar flow.

Supersonic Short Takeoff-Vertical Landing Attack Aircraft

There is no current aircraft type having the capabilities envisioned under this vehicle concept. The F-15 and F-16 are supersonic-capable surface attack aircraft, but they do not have short takeoff-vertical landing capability. The AV8B Harrier has a STOVL capability, but it does not have a supersonic capability.

Projected advances in technologies for propulsion, structures, and guidance-navigation-control systems provide a basis for an advanced air-to-surface attack vehicle concept that would have both a supersonic (Mach 2) and a short takeoff-vertical landing capability. The vehicle would be capable of 24-hour per day operation under virtually all weather conditions.

The advanced supersonic STOVL aircraft concept envisions a vehicle with reduced detectability to radar, infrared, visual, and acoustic sensors, and ability to use terrain following/terrain avoidance/threat avoidance techniques at low altitudes (less than 100 feet) to maximize survivability. Maximum speed at low altitude would be about M = 1.2. Artifical intelligence via onboard computers and sensors would provide the aircraft crew with a total "situation awareness" of threats, targets, and battle management information. The aircraft would be capable of being operated in a remotely piloted mode. The aircraft would have a Mach 2 capability at higher altitudes (above 10,000 feet).

Advancements in key technologies would be exploited to provide an estimated 10 percent reduction in life cycle costs and a 50 percent or more reduction in maintenance hours per flight hour relative to current fighter aircraft. Greatly enhanced reliability, availability, and operational sorties would be realized through use of fault-tolerant/reliable/reconfigurable major subsystems (propulsion, flight control, weapons, and avionics).

In the supersonic STOVL attack vehicle concept, the pacing technology will be the propulsion system for vertical lift with cruise/maneuver compatibility. Many possible propulsion/airframe concepts could be considered, such as lift plus lift/cruise, remote augmentor lift system, ejector thrust augmentors, tandem (split) fan or fan-in-wing. In a vertical and short takeoff and landing (VSTOL) aircraft, weight is particularly critical making the thrust-to-weight ratio of the VSTOL engine a key parameter. Projected technology developments would support a VSTOL lift/cruise engine with 15 to 1 thrust-to-weight ratio and lift (short duration) engines with 25 to one thrust-to-weight ratio. These levels of performance will dictate high temperatures in the engines to extract maximum thrust.

The advanced VSTOL airframe structure concept places a premium on the structure's being lightweight. Temperature requirements, except near the engines, are not expected to be critical. Heavy usage of

high-strain-ratio composites, thermoplastics, advanced metals (including powder metal/rapid solidified technology) would be essential. Active flutter suppression may be necessary for lightweight, flexible structures.

Guidance-navigation-control technology advancements combined with careful attention to human factors aspects would be key to handling the extremely high workload environment associated with low-level/high-speed penetration and attack. One possibility would be a flight safety override system that would take over control from the pilot when it sensed pilot incapacity or that the aircraft was in danger of flying into the ground.

Long-Range Supersonic Cruise Missiles

The use of variable flow propulsion systems and high lift-to-drag ratio aerodynamic shapes would provide a missile having two to three times the stand off range capability of current air-to-ground or air-to-air missile systems. Nominal cruise speed would be about M = 4.0; the missile would be powered all the way to the target and maneuver at high gs if so required. Its survivability and accuracy would allow conventional warhead or kinetic energy penetrators to be used on very hard targets, thereby raising the "nuclear threshold." In a large-scale version, this system would be employed as an intercontinental cruise missile.

Vehicle Types--Mach Range 5 to 12

The fourth group of vehicle types covers the range of Mach number 5 to 12 and includes both aircraft and missiles.

Hypersonic Aircraft and Missiles

There are no current vehicles having capabilities equivalent to those envisioned for the hypersonic aircraft and missile concepts, although there is, at present, a technology base in high-speed missile and target systems. For example, the Navy has under development ramjet-powered supersonic low-altitude target and other long range air battle missiles.

A vigorous, high-speed, airbreathing propulsion technology program pursued throughout the 1980s and 1990s would make feasible a number of types of hypersonic vehicles of which the following are illustrative examples.

Hypersonic Interceptor Missile (Mach 8 to 12)

This would be a supersonic combustion ramjet (Scramjet)-powered missile designed for a quick reaction capability to intercept aircraft targets at long range before the intruder can launch its missiles. The interceptor missile would have both a high-altitude mission capability as well as a high-speed/low-altitude penetrator mission capability at Mach numbers above 3.

Hypersonic Fighter/Interceptor

This is envisioned as a manned system flying at Mach 6 to 8 for an intercept at a range of 1,000 miles or more. It would be armed with advanced missiles or lasers. One mission would be to intercept penetrating high-speed bombers before they are able to launch their missiles. In a scaled-up version, this type of vehicle would serve as a first-stage launch platform for a rocket-boosted transatmospheric vehicle that would operate in suborbital flight or low earth orbit.

Key technologies for development of the capabilities under this vehicle concept involve both the propulsion system and its integration with the airframe, as well as high-temperature structures. The propulsion system would be based on high speed-ramjet technology, involving either subsonic and/or supersonic combustion.

A complex multilayer insulated or hot structure would be required. For the hypersonic fighter/interceptor, there is the added complication of multiple reusability and system life/maintainability. Extensive use of carbon-carbon composites, ceramic materials, and exotic metal alloys would be required.

Vehicle Types--Mach Range 8 to Orbital Velocity

The final group of vehicle types, Mach number 8 to orbital velocity, is best exemplified by a transatmospheric space vehicle.

Transatmospheric Vehicles

The closest current equivalent system to the transatmospheric space vehicle (TAV) is the space shuttle, but its flexibility and performance fall short of the potential capability envisioned for a transatmospheric space vehicle that would be operational beyond the year 2000.

A small, highly flexible transatmospheric vehicle can be conceived that would allow rapid access to and recall from low earth orbit or suborbital hypersonic flight. The simplest, most readily feasible

concept would utilize rocket propulsion, but airbreathing propulsion systems would be feasible in the far term. The TAV would be fully reusable with no refurbishment between flights and with maintenance requirements similar to those of high-performance military aircraft. The TAV would serve as a rescue vehicle for the space shuttle or the space station.

With a high lift-to-drag ratio (approximately 3.0 at reentry velocities), the TAV could be recalled in less than three hours from an arbitrarily inclined low earth orbit to a landing in the continental United States; there would be no need to wait for the orbit to change to a favorable location for reentry. The TAV would operate at a radius of action of 10,000 miles (global coverage) and return to the United States in two hours. The TAV would be extremely survivable as a result of its high-speed, high-altitude, and unpredictable maneuvering.

Several critical technologies underlie the TAV concept. An airbreathing TAV is considered feasible. For example, a hypersonic ramjet having a specific impulse in the range of 1,000 to 2,000 seconds might be considered a reasonable possibility. However, insufficient design work has been accomplished to assess accurately the technology needs of this option. The following key areas are relevant to a rocket powered TAV.

- High-temperature structures are needed for high-lift-to-drag-ratio maneuvering reentry vehicles, which would fly a very broad reentry corridor compared to the current space shuttle. The structure would be a complex multilayer design using exotic materials such as carbon-carbon composites. The substructure may be advanced organic or metal matrix composites or advanced aluminum and powder-metal alloys.

- Efficient, high-lift-to-drag ratio blended body aerodynamics are required for controlable reentry with a large cross-range/down-range footprint. This is a key technology area for an effective, flexible TAV. Accurate aerodynamic heating methods must be developed to design the flight vehicle for safe, controlable reentry.

- Improved rocket propulsion systems are needed to provide higher performance, more reliability, reusability, and a throttleable capability.

Systems Integration as a Discipline

The Systems Integration Panel was charged with the additional task of exploring the current state of knowledge of systems integration as a discipline and to project anticipated advances in this area. A

definition of systems integration is offered, and the discipline is identified with aeronautical design. There follow comments on design, in general, and on the state, progress, and need for advancement in systems integration.

It is observed that systems integration has progressed and is prospering reasonably well in the aerospace industry. It is noted, however, that systems integration as a discipline could yield substantial additional benefits in the field of aerospace research. Two areas related to research are highlighted:

- the need to identify research that is not taking place but is needed to exploit current technological breakthroughs; and

- the need for integration experiments--in particular, flight testing--as a total system verification tool.

For the purpose of this report, systems integration is defined as the activity that pulls together scientific, engineering, business, manufacturing, and other information to define and develop an aircraft. Specifically, this must be in adequate detail for the aircraft to be assessed correctly by independent experts and constructed eventually. By this definition, systems integration is the discipline of aeronautical design. This, in turn, is a specialized application to aircraft of the art of engineering design.

Design is a more general art than aeronautical design. It includes aeronautical design as a subset. Whether applied to a single bolt, an aircraft, or a space station, the thought process is essentially the same combining scientific data gathering and investigations together with imagination and intuition. Thus, it is both a science and an art. Because the thought process is common to the design of the simplest component and to the design of the most complex aircraft, engineers have been trained in the art of design by starting with simple projects or with small, well-defined portions of larger projects.

A complete, sufficient set of requirements for successful design cannot be defined because it is application-dependent. An essential requirement, however, is possession and understanding of the scientific data base that is needed to affect the design. In the specific area of the design of a new advanced system the data base must include the latest in technological knowledge. Generally, aircraft design teams are organized around groups of specialists, each group containing several experts in their respective field. However, to effect a successful design, it is essential that at least a subset of these experts be knowledgeable in several of the relevant technological disciplines. Thus, experts in propulsion must be near- experts in aerodynamics, materials, subsystems, fuels, computing, dynamics, etc. In addition, experts must be knowledgeable in the ways that aircraft go together.

Industrial design groups operate routinely with teams of such experts. The magnitude of the project determines the size of the group. Presently, large sets of data are transferred routinely by computer.

Substantial progress has been made worldwide in industry in systems integration. The progress has not manifested itself in the reduction of the size of the design group but rather has made possible the design of more advanced systems in a given time and with fewer mistakes being made in the development. A striking example of the improvement has been in the far more careful preflight testing that has characterized post-World War II aeronautics. This has yielded a most tangible and important benefit. In the pre-World War II era, test pilots were killed accidently almost routinely in the development of new advanced systems. Now, fortunately, that is no longer the case at all. In addition, recent systems, since about 1970 in particular, have met performance goals at first flight. This used to be an exception.

One of the major advances of modern systems integration has to do with the length of time it takes to build a new commercial airplane or engine. Despite the increased sophistication of modern systems, the time taken from go-ahead to certification is not taking any longer. It is typically five years for an engine and four years for the airplane. At the time of go-ahead, technology readiness must have been completely in hand for a period of about one to two years to allow establishment of system requirements under realistic technological ground rules. Thus, the time from technology readiness to entry into service of a new commercial system is from five to seven years. Limiting the length of the work to that period has been considered essential for cost control. Because of less efficient procurement and management processes, the above cannot be generalized to include government projects. It is hoped that advances in systems integration will assist in reducing the time it takes for such projects to mature.

Thus, the general state of the art of systems integration in industry is good and making continuous progress. Industry has been training its own personnel by what have now become routine traditional procedures. The current problem lies with the universities where design as a discipline often is not taught effectively. This, in turn, has led to problems in research organizations where the lack of systems integration activity has led to a great deal of wasted and uncoordinated research.

It is in the areas of research and technology development that the application of systems integration discipline could lead to new, fruitful results. To a large extent, researchers must be given freedom to pursue breakthroughs in a more or less unconstrained way. The role of systems integration as a discipline in research is to track each individual breakthrough and to seek means to bring together their combined benefits in terms of complete systems.

An important, almost crucial, aspect of this activity is to identify the "missing link." That is, specifically, research that is not being done to complement other breakthroughs and to make achievable feasibility of the complete system. Lack of emphasis on the "missing link" was exemplified in the post-World War II era by a large number of unsuccessful bomber, transport, and fighter projects that failed because the swept-wing had not been combined with the jet engine as a feature of these early systems. Introduction of the B47 airplane made this quite obvious.

Another important area where it is hoped that advances in systems integration will make research more effective is in the field of testing in general and integrated flight testing in particular. It is important that the results of flight testing address every question associated with a new technological concept. A partial set of data has little value because it would not be applied. In summary, significant advances and benefits can be expected from the application of systems integration discipline to research and technology functions.

APPENDIX

Panel Comments on Research and Facility Needs

In the course of their study and preparation of their reports, the panels gave some consideration to research and facilities needed to support the projected technological advancements in their respective areas. Although the panels were not specifically asked to provide such information, its possible value as guidance for aeronautical program and facilities planning purposes was deemed sufficient to warrant its inclusion as an appendix to the main report.

Aerodynamics

The Aerodynamics Panel identified several areas of research that should receive attention. Turbulence modeling should continue at several levels of hierarchy including both classical and nonclassical approaches based on physical insights gained from experiment. Care should be taken to determine the range of applicability of the models. The physics and effectiveness of viscous control devices and techniques need to be understood. The relationship between the flow structure and acoustic emissions need to be explored. Separation fundamentals in both steady and unsteady flows need to be determined. The nature of 3-D separation and reattachment plays a key role in drag reduction, rotorcraft design, and real-time response for supermaneuverability in fighters.

Transition fundamentals are required. The role of background disturbances should be understood and an amplitude/3-D spectrum criteria developed for transition prediction. Active and passive controls of transition for complicated flows should be developed.

New physical insights on vortex formation and dynamics are required; issues of importance include vortex generation and stability, active and passive vortex control, impact on acoustic source generation, and interactions between vortices.

The projected advances in aerodynamics presented in the panel's report are implicitly related to continuing utilization and improvement of existing experimental and computational facilities. Basic to many of the projected advances is a greatly improved understanding of fundamental flow physics to be gained by using new noninterfering techniques of flow visualization and measurement and the utilization of advanced computational capability. A large-scale supercomputer facility that utilizes the most advanced state of the art is required.

In addition, consideration should be given to the construction of a special purpose computer for time-dependent integration of the full Navier-Stokes equations. Computer hardware advancements will make

such a facility feasible using hardwired algorithms and massive parallel pipelined processing. A revolutionary jump in knowledge would be accomplished with this capability.

Existing ground test facilities will continue to provide the springboard for advancing aerodynamic technology. Continued emphasis on modernization of these facilities to improve productivity, data acquisition, and data accuracy is essential. In order to achieve the aerodynamic goals into the twenty-first century, maximum advantage should be taken of interactive coupling of CFD with the wind tunnel to increase the effectivity of ground testing. Strong consideration should also be given to unobstrusive instrumentation to observe flow field details, unobstrusive model mounting (magnetic suspension, for example), and adaptive wall technology.

Most propulsion research usually requires a progression of scale from small conceptual tests to full-scale development tests. The upper end of the size spectrum is not met by any existing NASA facility. A need exists for a large variable density test facility specifically tailored for propulsion related testing. Such a facility should also be capable of meeting general testing requirements in other disciplines from acoustics to icing.

Increased emphasis on hypersonic aircraft development poses a need for an advanced test facility. A unified facility capable of simulating flows from Mach 7 to 21 using a variety of test gases is required for developing configurations and measuring flow field details. Some facilities currently mothballed will need to be reactivated to meet the hypersonic research needs.

Propulsion

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Structures

Significant contributions have been made by NASA in structures research and technology development working with the aerospace industry in its successful design and development activity. However, the panel believes that the potential benefits of further structures research and technology development applicable to vehicles for the year 2000 warrant increased effort in selected areas.

- The need remains to continue near-term systems demonstration programs for advanced concepts that emphasize new design and manufacturing concepts; in particular, the utilization of CAD/CAM computer-aided design and manufacturing techniques should be emphasized to achieve high productivity and low-cost manufacturing.

- The development of integrated analysis and design methodology which makes use of new computational technology is needed to advance the technology. This includes development of new solution strategies as well as data management concepts for the tracking and control of design information.

- Adaptive structures represent the natural technology evolution for control of vehicle aeroelastic response. This is high-risk research that must be supported and entails the full spectrum of technology development tools: new analysis methodology, sophisticated wind tunnel testing, and ultimately flight testing.

- Basic structural research and interdisciplinary analysis efforts should be strengthened to establish the proper balance among fundamental research, interdisciplinary methods, and aeronautic systems demonstration programs through the year 2000.

- New solution strategies should be developed for integrated (multidisciplinary) analysis and design methods based on the future computational environment.

- Large-scale aeronautic systems demonstration programs for advanced structural concepts should be continued to include consideration of novel designs and low-cost manufacturing methods.

- National capabilities should be established for design and evaluation of advanced hot structures/thermal management concepts and adaptive structural configurations.

The Panel on Structures believes that two new facilities are needed. Advancements in thermal structures requires the establishment of a new test facility. The facility needs the capability to test instrumented structural components under combined mechanical/thermal loads with reduced atmosphere and temperatures approaching 3500°F. In addition, the facility needs to permit tests and evaluations of

passive and active thermal management systems, such as heat pipes, under combined thermal and mechanical loading cycles. This is an essential tool for the design and development of aircraft and missiles that operate at very high speeds.

Advanced propulsion concepts require solving structural dynamics/-flutter problems of turbine engines and turboprops. A new facility is required that will permit full-scale engine and turboprops dynamic testing, including the validation of new analytical methods needed for advanced propulsion concepts.

Materials

The Materials Panel identified the following areas deserving increased emphasis in planning future materials research and technology development activities.

- o High-temperature ceramics and composites for engine applications are areas with high potential benefits. Ceramics and ceramic composites offer at least a 260°C temperature advantage beyond that of the current superalloys. The ceramic composites have a strength advantage over ceramics and are more tolerant to flaws and thus potentially more reliable.

- o Fiber-reinforced high-temperature alloys offer about 150°C improvement in themselves and combined with thermal barrier coatings could provide high-temperature competition for the ceramics--perhaps with shorter development time and risk. Other options such as advanced "super" single crystals with thermal coatings could provide a nearer term payoff. Finally, very high temperature polymers offer a wide range of propulsion system and structures applications.

- o Effort should be expended to initiate work in a new field--discontinuous micromechanics--the interface between continuum mechanics (such as used in fatigue and fracture prediction, and structural analysis) and microstructure. This effort would require powerful computer assistance to handle the complex calculations involved as well as human resources capable of conducting analyses of high-temperature elastic-plastic materials. If successful, a bulk material microstructure could be selected which would render properties as close as possible to those desired for specific applications. An advance of this type could significantly shorten the time required to develop and qualify a new material.

- o Effort should be made to further advance the development of

  -- high stiffness fibers with good strain capabilities for resin composites,

-- three dimensionally reinforced composites for toughness improvement, and
-- a low-cost metal matrix material for airframe applications.

To support the necessary R&T activities, the Materials Panel recommends the establishment of three laboratories:

- A ceramic science laboratory in which powder and other precursor materials can be processed and fabricated into useful components under a wide range of conditions including ultra high temperatures for microstructural tailoring;

- A processing science laboratory for high-temperature metals and related composites. This facility would contain a variety of advanced fabrication equipment, but would emphasize molecular/atomic level consolidation. Such a facility would support a wide range of materials research and technology developments from structural materials to electronic and optical materials; and

- A hot composites laboratory in which to undertake such work as computer-aided pilot line fabrication and engine simulation under realistic stress, cycle, temperature, and other environmental conditions.

Guidance, Navigation, and Control

The research and technology developments required in guidance, navigation, and control are substantial. However, the panel believes the benefits and payoffs in performance, capability, and cost savings justify an increased research and development effort. Examples of research and development needs in this area include:

- Development of credible and usable models for use in multidisciplinary design of highly interactive systems. High-fidelity models are required for:

  -- dynamic response of aeroelastically tailored structures,
  -- unsteady aerodynamics at high angle of attack,
  -- interactions of engine/inlet/nozzles, and
  -- pilot command/external disturbance environment for highly augmented aircraft.

- Development of computer-aided design methods for efficient multi-input, multi-output control for a large number of control effectors, with "practicalization" algorithms for simplifying complex state feedback mechanizations.

- Formulation of credible flying-qualities criteria for "super-augmented" aircraft, using high-authority digital flight control systems.

- Development of architectures that provide the ultra high reliability and reconfiguration requirements demanded by flight crucial systems as well as the supporting test and assessment tools to establish that the fault-tolerant design has actually been achieved.

- Development of practical real-time concurrent distributed processing techniques and design methods.

- Development of high-integrity system and software verification and validation methods that are less subjective than current methods and which exploit automation technology available.

- Development of practical optimization algorithms that can act on large data bases in near real time to aid the pilot in flight path and flight systems decision making. This may also involve non-classical computer architectures.

- Development of systematic techniques for task allocation among crew and vehicle systems based on mission requirements and human error theory.

- Development of simulation tailoring methods for tasks/systems to duplicate flight-obtained human response dynamics.

Because of the highly interdisciplinary nature of this work, new organizational approaches will be required along with analytical wind tunnel, simulation and full-scale flight research to develop effectively the technology for application.

Table A-1 presents a summary of some of the more important future GNC research and technology development needs identified by the panel. Support of this class of activity is deemed necessary by the panel if advances in aircraft performance, operations, capability, economy, and safety are to be realized by the year 2000.

To advance guidance, navigation, and control, the panel felt that new ground-based facilities are needed and must be identified and defined as soon as possible because of the long lead times related to budget approval and construction. In addition, existing research aircraft are limited with respect to fulfilling the needs of interdisciplinary research programs where the aerodynamics, propulsion systems, structure, and GNC systems are all critical players. New research aircraft are essential to develop and mature this new technology. As aircraft systems become more integrated, interactive and embedded in the vehicle design, new ground facilities will be required to support

TABLE A-1 GNC Research and Technology Development Needs

R&T Area	Needs
Multidiscipline systems integration methodology	o Interdisciplinary design teams to integrate "smart" structures/propulsion/aerodynamics o Concept development/design methodologies for diverse, hierarchical controls with inherent reconfiguration capability o Technology (hardware/software) development for multiple, embedded subsystems
Active subsystem control	o Active propulsion, aerodynamic, and structures effector control concepts o Accurate and manageable models of aircraft elements/environment o Design procedures/algorithms
Automated situational information management systems	o Tactical, target, and terrain data analyses o Real-time trajectory generation algorithms
Pilot vehicle interface: systems, design, simulation	o Human performance theory/design methodology to reduce susceptibility/incidence of human errors o Displays/controls to enhance information transfer between onboard systems and crew o Allocation of functions to crew/vehicle systems o Validated simulation facilities with appropriate fidelity for evolution of requirements, and system assessment o Flying quality requirements and design criteria for superaugmented and novel aircraft
Global cooperative airspace management system	o Algorithms, procedures, and system architecture for airspace management o Global cooperative satellite-based surveillance and air/ground communications component technology o Four dimensional (4-D) aircraft/air traffic control (ATC) systems integration

TABLE A-1 (cont.)

Ultra fault tolerant and reliable systems	o Architectures for ultra fault-tolerant systems o High-integrity and automated methods o Reconfigurable control methods o Systems highly immune to EMI/EMP o Reliability/integrity assessment tools o Redundancy management technology
Design and validation oriented software	o General GNC computer-aided design technology o Automatic generation of trustworthy flight code from high-level system design specifications o Real-time, concurrent, distributed processing systems
Onboard aiding systems	o Massive data base storage and access o Nonclassical computational architectures
GNC sensors	o Micro, conformal, force sensor arrays for active flow/structure controls o High reliability, rugged, nonintrusive position, velocity, flow, temperature and force measurements for embedded engine controls o High-reliability angle of attack and sideslip sensing or estimation o Air data for extreme envelope flight o Obstacle sensing
Aircraft power and actuation systems	o Fault-tolerant power system concepts o Highly reliable electrical and hydraulic power transmission and distribution systems o Reliable, high-bandwidth electrical and hydraulic actuators for diverse interactive subsystem applications

the flight testing of these research aircraft.

The following specific recommendations are given:

- o maintain the state of the art in manned flight simulation with the computational ability to model the multiple sensor sources and more extensive fault-tolerant system characteristics faithfully in real time. This may require new approaches to model implementation and computing architecture;

- o provide for the inclusion of actual GNC hardware in ground simulations of GNC systems and the ability to operate the complete research aircraft in closed-loop simulation;

- o utilize supercomputer resources for analyses of GNC problems and development (e.g., global cooperative airspace management system modeling and analysis);

- o maintain modern fixed and rotary wing aircraft testbeds for GNC flight research to provide validation and exploration capability, especially critical for flight controls, systems integration, and pilot-vehicle research. Ground facilities to support advanced systems research aircraft also are required;

- o maintain research aircraft capable of interaction with experimental ATC systems;

- o maintain man-machine research laboratories that can address fundamental physiological and psychological research issues in the context of realistic vehicles, systems, and missions; and

- o provide for simulation of interactive multi-aircraft operations for military or civil missions.

Finally, the panel notes that the multidisciplinary integrated systems design technology identified in this report represents a new dimension to an old discipline. A sound research and technology base program in conjunction with flight research is mandatory to move this discipline into the arena of practical design and development required to meet AD 2000 targets. In considering the historic development of other new disciplines, it is clear that a combination of R&T base and actual experimental multidisciplinary design and development programs must be established. The recommended approach to addressing this multidisciplinary dynamic systems integration is to:

- o Carry out full scale flight experiments

  -- Conduct partial integration experiments on modified <u>existing vehicles</u>.

-- Conduct full integration experiments on new (X-series) vehicles.
-- Conduct full integration experiments on new (X-series) system.
-- Organize networks and teams to achieve system integration and to develop skills.

o Focus on integration challenges such as:

-- Partial integration examples
- Integrated flight/propulsion control
- Active aero and flexible wing control

-- Full integration examples
- Multimission VTOL/rotorcraft
- Transatmospheric/space vehicle.

There is the need for truly correlated facility experiments. Too often, research is conducted using simplified models without the accompanying validation of these results in the real environment. Correlated analytic, laboratory, and flight results will provide the strongest and most credible data base so vital in the complex GNC issues discussed in this report.

Computer and Information Technology

The special requirements of the aeronautics community with regard to computer and information technology must be identified and given special attention if they are to be met. The Panel on Computer and Information Technology compiled the following list summarizing the most critical technical barriers and research challenges pertinent to the special requirements of aeronautics.

o Components - The effective logic density within a system must continue increasing in order to achieve the projected system performance capabilities. Continued advances in this area are critically dependent on development of new circuit technologies since current techniques will reach their physical bounds by the early 1990s. As densities increase, heat dissipation will become an even more critical problem.

o High Integrity - Major advances in the integrity of components, architecture, software, algorithms, and human interfaces are required. The areas of software, algorithms, and human interfaces will require special attention.

o System Architecture - Development of memory systems for the future distributed and super speed machines (including high-performance transfer paths and large capacity, long-term mass memories) will be needed.

- Software - The performance and integrity issues imply the urgent need to better manage issues of complexity in the large software systems of the future. The growth in the ability to devise, design, and write complex programs has far outstripped our ability to verify, test, and modify such programs.

- Human Interface - Major advances are needed both in display resolution and in speech communication.

- Artificial Intelligence and Expert Systems - The terms artificial intelligence (AI) and expert systems easily can be misunderstood by those not acquainted with these technologies, leading to a propensity for misapplication. The divergence in the rate of improvement in the ability of equipment to support the complexity in AI systems compared to the growth of application complexity will prevent indefinite scaling of these systems. Developments in the area of theorem provers must focus on verification and validation for aeronautics if the needed technology is to be developed.

Implementation of the complex aeronautical information processing systems envisioned for the year 2000 and beyond is more likely to be limited by communication, control, software development cost, and verification/validation cost than by hardware component capability or affordability.

Human Factors

The Panel on Human Factors identified several major research issues that need to be addressed.

- Human error tolerant systems. Emphasis should shift from focusing solely on reducing the frequency of human errors (which, in the extreme, might be counterproductive). Approaches should be developed that will allow humans to respond flexibly and innovate when necessary, while helping them to detect their own errors quickly, reverse their actions if possible, and in general avoid the negative consequences of errors without being constrained inordinately by such things as procedures and interlocks. The research necessary to support such approaches includes basic studies of the causes and contributing factors associated with human error in aeronautical systems, as well as methodological developments for analysis, classification, and interpretation of human error.

- Adaptive aiding and dynamic task allocation. The increasing power and sophistication of computer technology are leading to aeronautical systems of sufficient "intelligence" to make the tasks allocation problem less than straightforward; there are many tasks that could be performed acceptably by either computers or humans.

This capability will make it possible to perform task allocation on-line, taking advantage of the information processor (computer or human) that is likely to perform better at any particular point in time. To realize such benefits, considerable research will be needed on human performance modeling (particularly in multi-task situations) and human-computer communication techniques.

- Interaction of artificial and natural intelligence. This is viewed as encompassing much more than human interaction with the currently popular "expert systems." In fact, the panel felt that the whole issue of "expertise" needs much more attention, particularly in terms of inherent differences between machine and human expertise. It was concluded that these differences will impact substantially the extent and level of communication that is required between the two types of intelligence. A related, and almost philosophical, issue is the notion that only "authority" but not "responsibility," can be allocated to computers. The plausibility of this assertion should be studied; it has profound implications for answering the question: "Who is in charge?"

- Integrated system design methodology. The panel felt that the productivity and costs of manpower should be considered throughout the system life cycle. Thus, the human factors of design, operations, maintenance, and management should be viewed in an integrated manner. Research is needed to develop, validate, and implement more systems-oriented approaches to aeronautical systems design and evaluation; the current, much more myopic view of manpower issues almost certainly leads to inefficiency and less than full effectiveness.

- Interdisciplinary trends. In the recent past, the disciplines of engineering, computer science, and psychology were the primary contributors to man-machine systems efforts in aeronautical systems. More recently, hybrid fields of human factors, cognitive science, and artificial intelligence have come to the fore. The future appears to be headed to an amalgam of these three hybrid disciplines into a new area which, for want of a better term, can be called "cognitive engineering." These interdisciplinary trends need special support. Despite their great relevance to contemporary aeronautical systems problems, they are not supported inherently by most universities. Outside support will be needed for these interdisciplinary trends to prosper.

The Panel on Human Factors made the following assessment of the resources required--facilities and personnel--to support the recommended research program.

- High-fidelity simulators. Cockpit flight simulators should include a capability for helicopters and for general aviation. These simulators should be highly modular and capable of flying inter-

actively. Issues such as crew complement could be investigated by changing the basic configuration of the cockpit.

- Part-task simulators. Part-task simulators, having neither motion nor visual systems and possibly nothing more than computer terminals are necessary for performing research on human/computer interaction including display formatting, information strategies, and expert systems.

- Air traffic control (ATC) simulation. Adequate simulation of ATCs will be necessary to provide an input to the cockpit simulators and part-task devices described above. This simulation must be capable of integrating with several aircraft simulators or part-task devices simultaneously.

- Advanced computer systems for simulation. The development and application of advanced, standardized, real-time operating and development system environments, and the concurrent development of high-computational-bandwidth hardware will be required to provide the computational support for the simulation facilities just identified. The widespread application of these advanced simulation systems will facilitate the coordination of related research programs both within existing organizations and with other government, university, and industry laboratories.

- Basic human performance laboratories. Facilities to support basic research in visual perception are required to develop criteria for cockpit displays and visual simulation. Facilities should be developed to support physiological and cybernetic research.

- Other required research capabilities include instrumented aircraft, voice recognition laboratories, and multiple, low-cost research simulators that could be used at universities, military laboratories, and aircraft manufacturing plants.

- Human factors professionals. The required research focuses on a multidisciplinary human factors technology base. Competent human factors researchers with relevant training and experience for aerospace research are in low supply and high demand. Such personnel must form the core of any team that can conduct the recommended research and successfully develop the technology. Action should be taken to help assure such people are available in the required time frame through training and research grants to suitable universities. It should be recognized that the skills required by human factors professionals are changing. Computer science is becoming a requisite skill, as is a strong background in quantitative analysis.

- Interdisciplinary teams. Training the "cognitive" engineers of the future will require entirely new, interdisciplinary, interdepart-

mental programs. Human factors professionals cannot do the job alone. The interdisciplinary teams will include human factors experts, computer scientists, operations experts, control engineers, and artificial intelligence specialists. Computer science programs, while developing expert systems technology, also should develop some expert systems in the cockpit context. This could benefit both programs.

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GLOSSARY

AI	Artificial Intelligence
ATC	Air Traffic Control
BPR	Bypass Ratio
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CCV	Control Configured Vehicle
CFD	Computational Fluid Dynamics
C_f	Friction Drag Coefficient
COOP	Cooperative Control
CPU	Central Processing Unit
CR	Counter-Rotating Propellers
CTE	Coefficient of Thermal Expansion
DAST	Drones for Aerodynamic and Structural Testing
DN	Measure of the speed of rotation of a ball bearing
E	Modulus of elasticity
FET	Field Effect Transistor
FMS	Flight Management Systems
Gbits	Gigabytes
GFLOPS	Billions of Floating Point Operations Per Second
g-load	Weight to indicate increase in g's
GNC	Guidance, Navigation, and Control
gs	Acceleration equal to acceleration of gravity
GPa	Gigapascals
GPS	Global Positioning Satellite
GWords	Billions of Words Per Second
ICFM	Internal Computational Fluid Mechanics
IPN	Interpenetrating Polymer Networks
J/m	Joules per Meter
K_{IC}	Critical Fracture Toughness
L/D	Lift Over Drag
LDA	Laser Doppler Anemometer
LEX	Leading Edge Extension
LFC	Laminar Flow Control
LSI	Large Scale Integration
M	Mach Number
Mbytes	Megabytes
MIMD	Multiple Instructions, Multiple Datastream
MIPS	Millions of Instructions Per Second
MLS	Microwave Landing System
MMC	Metal Matrix Composites
MN/m^2	Meganeutons per Square Meter
MPa	Megapascals
Mpsi	Millions of Pounds per Square Inch
MWords	Millions of Words Per Second
NASTRAN	NASA Structural Analysis program; a general purpose finite element computer code

Glossary (cont.)

Navier-Stokes equations	Equations of motion for a viscous fluid
NDI/E	Nondestructive Inspection and Evaluation
NDT	Nondestructive Testing
NOE	Nap of the Earth
PEEK	Polyetherether Ketone
pixel	Picture Element
P/M	Powder Metallurgy
PMR	Polymerization of Monomeric Reactants
PPT/Nylon	Parapolyphenylene Terephthalate/Nylon
psi	Pounds per Square Inch
PSZ	Partially Stabilized Zirconia
RAM	Random Access Memory
RPV	Remotely Piloted Vehicle
Reynolds Number	Ratio of momentum forces to viscous forces
SR	Single Rotation Propellers
STOL	Short Takeoff and Landing
STOVL	Short Takeoff and/or Vertical Landing
TAV	Transatmospheric Vehicle
TPS	Thermal Protection System
TR/TV	Thrust Reversing/Thrust Vectoring
TS	Tensile Strength
VHPIC	Very High Performance Integrated Circuits
VHSIC	Very High Speed Integrated Circuits
VHSIP	Very High Speed Information Processing
VLSIC	Very Large Scale Integrated Circuits
VRCT	Voice Recognition/Computer Translation
VSTOL	Vertical and Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing

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